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Anat Zohar
Yehudit Judy Dori *Editors*

Metacognition in Science Education

Trends in Current Research

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Chapter 1
Introduction

Anat Zohar and Yehudit Judy Dori

Research about metacognition and its implications for learning and instruction have become a central issue in education. The call for teaching metacognitive skills is considered one of the three main implications for instruction that emerged from over three decades of research about how people learn; the two additional implications being: (a) the call for teachers to draw out and consider students' preexisting understandings, and (b) the call to replace superficial coverage of all topics in a subject area with in-depth coverage of fewer topics that allows key concepts in that discipline to be understood. Metacognition is significant across the curriculum and an emphasis on metacognition needs to accompany instruction in each of the school disciplines (Bransford et al. 2000).

There is ample evidence that metacognitive activities, or the metacognitive skills they emanate from, appear to be domain general by nature, rather than domain specific (see Chap. 2, this volume). Yet, the specific metacognitive knowledge required in each lesson varies according to the knowledge structure and specific content of the discipline (Bransford et al. 2000). In a history lesson, for example, students might be asking themselves who is the writer of a document, and how does that affect the interpretation of events. In biology, students might be engaged in monitoring their understanding of the relationship between structure and function of an organ. In chemistry, they may focus on monitoring their understanding of the

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micro- and macro-levels of the structure of matter, while in physics they may focus on monitoring their understanding of the correspondence between the details of a physical model and the results of the pertinent empirical experiment. This subject specificity suggests a need for a separate study of metacognition in different domains. Indeed, research about metacognition and learning proliferates in diverse areas (see Chap. 2 in this volume).

Although science education researchers have also been engaged in a considerable amount of work in the field of metacognition, to date there is still no book that examines this body of research. The goal of this book is to fill this void. The book consists of an introduction and ten chapters describing current theoretical and research-based trends concerning metacognition in science education. The opening and closing chapters (Chaps. 2 and 11) are theoretical. The eight middle chapters (Chaps. 3–10) are research based, describing studies in physics, chemistry, biology, and environmental education. The first part of the introduction reviews the ten chapters. The second part of the introduction discusses the various views of metacognition expressed in the eight research-based chapters and concludes with some final general observations.

Overview of Chapters

In Chap. 2, "Metacognition in Science Education: Definitions, Constituents, and Their Intricate Relation with Cognition," Veenman undertook the difficult task of providing a general introduction to metacognition and reviewing its role in science education. The task is difficult not only due to the vast number of studies about metacognition, but mainly because these studies do not support a coherent understanding of this concept. In fact, the literature points to multiple differences regarding the ways researchers view the essence of this concept, its various components, the interrelationships among its components, the relationships between the cognitive and metacognitive dimensions, and the developmental roots of metacognition. Veenman begins his chapter by acknowledging this difficulty: "One of the reappearing problems with metacognition research is the 'fuzziness' of the concept and its constituents. This fuzziness is not only due to a proliferation of terminologies. Researchers also disagree about the ingredients of metacognition and their interrelationships." Therefore, no concise introduction of the sort that is appropriate for this book can possibly capture all the different theoretical approaches to metacognition and to metacognitive research.

Still, Veenman's chapter succeeds in providing an organized, clear, and concise review of many of the main approaches that appear in the literature. First, a distinction is made between metacognitive knowledge and metacognitive skills. Metacognitive knowledge refers to the knowledge about the cognitive system, while metacognitive skills concern the regulation of cognitive processes. The historical roots, the nature of processes involved, the development and acquisition, and assessment methods are discussed for both concepts. Veenman then presents a comprehensive theory

regarding the interrelationships between the cognitive and metacognitive levels, describing the theory of metacognitive skills as self-instructions. Next, the role of metacognitive skills in science education is discussed from the perspective of how metacognitive skills are enacted in four types of learning processes: reading text, problem solving, inquiry learning, and writing. Some of the chapters in this book continue to develop the research of these learning processes in science education. For instance, Chap. 3 by Norris and Phillips and Chap. 8 by Herscovitz, Kaberman, Saar, and Dori examine the role of metacognition in reading and understanding scientific texts. However, as described in what follows, other chapters extend the scope of topics they address beyond these four learning processes.

In Chap. 3, "Reading Science: How a Naive View of Reading Hinders So Much Else," Norris and Phillips provide a comprehensive description and review of several previous studies, emphasizing what they have learned from these studies about the role of metacognition in reading scientific texts. Their work is situated in a paradigm discerning between two different views of reading. The simple view of reading emphasizes decoding words and information location. The more sophisticated view sees reading as inferring meaning from texts through analyzing, interpreting, and critiquing texts. In science education, this means that engagement with the text needs to address reasons and evidence for conclusions, and that these need to be integrated into the students' own cognitive worlds. The simple view of reading does not really address the deep goals we wish to achieve in science education. Yet, it is the more prevalent form of reading that takes place in science classrooms.

The more sophisticated type of reading requires extensive metacognitive thinking or more precisely the monitoring and control (jointly, the regulation) of thinking while reading. In order to understand a text, students must ask themselves questions that monitor their understanding, such as how well they understand a passage. If they realize that they do not understand, they need to instruct themselves to do something about it, hence the significance of the control function of metacognition for this process. It is precisely this more sophisticated type of reading that tackles the real meaning of "doing science" through interaction with texts. It is therefore imperative that science educators will understand the more sophisticated type of reading in depth, and study the barriers that hinder its successful learning.

The authors studied senior high school students who were taking or had completed an average of four senior high school science courses, and undergraduate university students who on average had taken eight additional terms of science beyond high school. The sample thus consisted of individuals who had more science background than the average high school or university student. The authors devised a set of interpretive tasks built around authentic popular reports of science that had appeared in mainstream newspapers and magazines. They then asked students questions requiring interpretations of the texts that went beyond the surface meaning. Students were then given two kinds of metacognitive tasks related to the monitoring function of metacognition: one task called for judgments about the difficulty of the texts to read, while the other required judgments about the effect of what they have read on their prior beliefs. These judgments can affect how readers subsequently control their reading, a point that the authors clarify through several examples.

The chapter presents data showing that the students who participated in these studies consistently made poor metacognitive judgments. The explanation for this finding is in students' epistemological beliefs about the nature of reading, i.e., that the poor results were generated by the fact that students possess a limited view of the nature and goals of reading. Therefore, they do not have an appropriate standard against which they can monitor their reading. Consequently, the control of their reading is also not effective. The implication of these studies is that if such poor performance is found among students with strong science backgrounds, the performance of other students must be even more problematic.

The authors of this chapter studied this central issue in a deep and convincing way. By addressing metacognition in reading science texts from the perspective of the sophisticated view of reading they support, they show interesting connections between four factors: research about reading science texts, reasoning and argumentation in science classrooms, students' epistemological beliefs about the nature of reading, and metacognition. In order to support the development of students' reading in the directions they outline, the authors conclude their chapter by proposing several practical recommendations for writing textbooks and for learning and instruction in science classrooms.

In Chap. 4, "Metacognitive Knowledge and Field-based Science Learning in an Outdoor Environmental Education Program," Schraw, Olafson, Weibel, and Sewing examine the relationship between metacognition, attitudes about a field-based science program and student learning in an environmental education program among 4th and 5th grade students. The study applied three research instruments. Prior to learning, students completed the 12-item Jr. Metacognitive Awareness Inventory (MAI), an instrument designed to assess metacognitive awareness. The study also applied pre- and posttest attitude and knowledge scales. Significant gains were recorded for attitudes and knowledge at each grade. Factor analysis repeated the findings of earlier studies, yielding two distinct and correlated factors: one corresponding to the regulation of cognition and the other to the knowledge of cognition. Metacognitive knowledge was correlated with attitudes and posttest knowledge scores, whereas regulation of cognition scores was uncorrelated with these measures at the 4th grade.

The findings confirmed that the knowledge and regulation of cognition factors are indeed two separate yet correlated constructs, and that these constructs can be measured in a reliable and valid manner. Another conclusion is that metacognition is positively related to increases in learning and attitude change, but that the correlation with metacognitive knowledge is more salient than the correlation with metacognitive regulation. This chapter makes two important contributions. The first is that the study took place with relatively young children, supporting the developmental view that metacognition develops earlier than previous researchers had often believed. The second contribution is that the study took place in a field-based program concerning environmental education, extending the research about metacognition and learning to two relatively new contexts: environmental education and field-based learning.

In Chap. 5, "The Role of Metacognition in Students' Understanding and Transfer of Explanatory Structures in Science," Grotzer and Mittlefehldt argue that in order to understand complex science concepts, such as density and pressure, one first needs an awareness of types of causal patterns and their features. These concepts have an underlying relational causality that students often reduce to simple linear explanation. Students are typically unaware of their assumptions about causal structures which are usually not addressed by most science curricula. In a sense, what is called for is a meta-structural knowledge, i.e., the ability to reflect upon and recognize particular forms of causal patterns.

This chapter explores the power of metacognition in helping students to reflect upon and revise their underlying causal assumptions to improve science learning. The authors introduced "metacognitive moves" into instruction about the nature of the causal patterns implicit in density and pressure-related concepts. The study took place in six 8th grade science classrooms with pre- and post-assessments, interviews, collection of students' writing samples, and key classroom observations. They found a high correlation between the number of metacognitive statements students made and higher post-assessment scores. Students who made more metacognitive statements on their density post-test showed more transfer of understanding from density to air pressure.

Previous work engaged students in reflecting upon the nature of the embedded causality in the science they were learning by introducing RECAST (REveal the underlying CAusal STructure) activities and explicit discussion of the causality involved. In the current chapter, the authors shifted responsibility for the reflective behaviors from teachers to students, with the hope that this would increase the likelihood of transfer. To this end, the metacognitive components applied in this chapter needed to go beyond encouraging *awareness* to include active *monitoring* and *evaluation*. Students also needed aspects of *self-knowledge* and knowledge of tasks. Awareness enables students to detect difficulties in understanding science concepts and to realize how faulty assumptions can distort the understanding of the concepts being taught. Monitoring is important in detecting how these assumptions interact with one's science concepts. Evaluation is required for choosing the most effective causal framing as students structure new concepts. Self-knowledge was promoted by encouraging students to examine their cognition for intelligibility, plausibility, and wide applicability. Assessing the intelligibility of a new idea (e.g., asking "does this make sense to me?") may include both intrapersonal and interpersonal dimensions, as students may be encouraged to reflect on other students' ideas or on the teacher's idea. All this requires *self-reflection* as well. In sum, the authors conclude that a metacognitive stance is necessary so that students would be able to apply the advanced causal patterns that are inherent in science concepts, without which deep conceptual understanding of concepts such as density or pressure is not possible.

In Chap. 6, "Self-regulated Learning and Conceptual Development in Young Children: The Development of Biological Understanding," Whitebread and Grau create and explore interesting connections between metacognition and several important other constructs: self-regulated learning (SRL), intentional conceptual

change, and motivation. The connection between SRL and metacognition, which had been an unresolved issue according to previous researchers, is explored in the chapter's introduction, where the authors state clearly and concisely how they view the relationships between these two concepts. According to their view, self-regulation is a broader concept than metacognition. Metacognition refers specifically to the monitoring and control of cognition, while self-regulation refers to the monitoring and control of a broader range of human functioning such as social, motivational, and emotional aspects. After embedding metacognition within the SRL construct, the chapter analyzes the relationships between these two concepts and models of conceptual change. The authors bring forth a model that views conceptual change as *intentional* (Intentional Conceptual Change or ICC), bringing together aspects of self-regulated learning and domain-specific knowledge acquisition. This is precisely the point where the empirical case study analysis described in the second part of the chapter comes in. Since there is still too little research on the relationships between the development of scientific concepts and learning and thinking skills (including SRL), in specific science domains (and particularly in biology), empirical study aiming at studying these relationships has significant value.

To address this point, Whitebread and Grau conducted a case analysis naturalistic study including eight cases belonging to 3rd grade students whose goal was to examine the relationship among SRL and the development of biological domain-specific knowledge. They investigated whether children exhibiting higher SRL skills show greater evidence of conceptual development, or vice versa. The data did not provide a simple relationship between these constructs, but some interesting suggestions could be extracted from the data. SRL and conceptual development were not manifested through the analysis as unitary concepts. Instead, children showed a great extent of variability. Also, the evidence from the analysis did not suggest a clear linear relationship between self-regulated learning and biological knowledge as a unitary concept. The analysis suggested that children who belonged to the "high" SRL group tended to perform at a high level in subject domains where the tasks required more complex reasoning skills, i.e., tasks in the contexts of classification of living things and in the context of interactions between living things and the environment. However, the same students performed at the lowest level (among all eight students) in a task that required mainly declarative knowledge. The chapter explores the implications of these findings for science education practice as well as for future research.

In terms of the concept of metacognition embraced in this chapter, the authors' views provide an analytical framework of self-regulated learning in context. The authors build on the classical distinction between metacognitive knowledge and metacognitive regulation processes. In the research presented in this chapter, metacognitive knowledge was not frequently observed by itself within the data collected, as the predominant type of behavior observed was of online regulation, namely, planning, monitoring, control, and reflections. Additional significant points to be noted about their view are the following: (a) the existence of overlapping area between metacognitive knowledge and regulation processes, delineating the intimate relationships between these two central metacognitive components;

(b) The existence of linkages between the two parts of the construct illustrates how metacognitive knowledge feeds the processes of regulation and vice versa; (c) that metacognitive knowledge and regulation processes interact not only with cognition but also with "warmer" aspects of human experience such as motivation, and socio-emotional aspects. Since as explained earlier, the authors believe these aspects are indispensible, especially in the more applicable context of classrooms, the focus of their study is actually self-regulation (which includes these aspects) rather than metacognition (that is limited to the cognitive aspect); (d) the assumption that the personal self-regulated learning of an individual is not an isolated process but is embedded within shared regulation of learning that involves dimensions of interpersonal, community, group cognition, and cultural and educational systems. This assumption is also reflected in how SRL is observed and interpreted in the research presented in this chapter.

In Chap. 7, "The Role of Self-Monitoring in Learning Chemistry with Dynamic Visualizations," Chiu and Linn explore how embedding visualizations concerning the topic of chemical reactions in the knowledge integration learning perspective contributes to students' learning. Their chapter addresses one segment in a comprehensive research agenda that had demonstrated the effectiveness of the chemical reactions modules in helping high school students make connections among representations and ideas compared to students receiving traditional, text-based instruction. The goal of the study presented here is to explore the hypothesis that the success of the module may be partly due to embedding the visualizations in a knowledge-integration pattern. The chapter focuses on the development of students' self-knowledge and self-regulation through self-assessment and explanation prompts.

The chapter describes two studies. The self-assessment study investigated how learners judge their understanding before and after generating self-explanations prompted by the instructional scheme. The study showed that students typically overestimated their understanding of visualizations and that encouraging students to explain and rate (assess) their understanding helps them realize gaps in their knowledge and judge it more accurately. The suggested reasons for these results involve metacognitive processes. The authors suggest that students interact with the visualizations and initially believe that they understand them. However, when they get to the explanation prompt, it forces them to make their thinking visible, to reflect on their understanding, to realize that they may not have understood the visualization as well as they previously thought and to identify gaps in their knowledge that could make their self-rating more accurate. The explanation prompts can therefore help students not only make connections in chemistry but also develop their monitoring, self-assessment, and self-knowledge, i.e., their metacognitive knowledge and skills.

If students know they do not understand a concept, they may or may not act upon these judgments to remedy gaps in their understanding. In the Revisiting study, Chiu and Linn investigated navigational logs of students progressing through the unit. They compared where students navigate after explanation prompts to where they go after other steps within the unit. Students revisit steps when they realize that

they are confused or do not understand something. Students' choice to revisit a step of the activity out of sequence is considered an indication of intentional activity. The authors therefore regarded these revisits as indicative of self-regulation and analyzed the conditions that elicited this kind of behavior. The results demonstrate that the most common revisiting pattern is from explanation steps to dynamic molecular visualization. These results suggest that eliciting explanations may help students identify what they do not understand (i.e., promote the monitoring and self-knowledge functions of metacognition) and encourage students to revisit visualizations to remedy gaps in their knowledge (i.e., promoting the regulation/control function of metacognition).

Chiu and Linn work is conducted within the general paradigm suggesting that technology alone is not enough to promote students' understanding. Rather, it is the embedment of the technology in a fruitful pedagogical framework that fosters learning. Specifically, the chapter's contribution is in characterizing *how* self-assessment and explanation prompts actually affect learning with technology by developing students' self-knowledge and self-regulation, i.e., by developing students' metacognitive thinking. The authors thus view the development of metacognitive thinking as a significant factor in explaining the way in which the self-assessment and explanation prompts actually improve learning with visualizations. From a methodological point of view, the main contribution of the chapter is in using the logging capabilities of the WISE 3.0 platform to capture students' intentional activities by analyzing when students choose to revisit a step out of sequence. The study thus represents the authors' first steps toward capturing self-monitoring instances with log data. Although, as the authors themselves state, their measures were quite simple, they provided insights into the possibilities of using this method in future research.

The notion of metacognition applied in this chapter involves some form of self-knowledge and self-regulation. In terms of self-knowledge, the chapter addresses knowledge about oneself as a learner, such as knowing what you do or do not know. In terms of self-regulation, the chapter addresses mainly monitoring, evaluating, and revisiting one's activities. In the Revisiting study, monitoring and evaluation processes affected self-knowledge (identifying the gaps in one's knowledge) which fed back into self-regulation, by revising cognitive processes (i.e., the choice to revisit steps in the activity).

In Chap. 8, "The Relationship Between Metacognition and the Ability to Pose Questions in Chemical Education," Herscovitz, Kaberman, Saar, and Dori describe a design and implementation of a metacognitive tool that was used by high school chemistry students in two related studies. Using this tool, the authors implement a taxonomy of questions classification. They embrace both knowledge and regulation of cognition for guiding students' ability to pose complex questions as a way to gain better understanding of adapted scientific articles.

In the first study, the Case-based Computerized Laboratory (CCL) environment exposed students to reading case studies and to metacognitive knowledge of question posing strategies. The three-component taxonomy includes content, thinking level, and chemistry understanding levels. It enabled chemistry students to assess the quality of the questions they had posed. Using semi-structured interviews,

the authors monitored metacognitive processes of six students who think aloud while posing their questions. During the interview, students analyzed their questions, explaining why they had posed those particular questions and how they had taken the different aspects of the taxonomy into consideration. They used metacognitive strategies for analyzing and monitoring self-posed questions by thinking level and chemistry understanding level, and by reflecting on the process of formulating each question.

The focus of the second study was on identifying the strategies students had used while reading adapted articles and on the influence of integrating the metacognitive tool on students' question posing ability. The research setting included one experimental and two comparison groups. The groups differed in the number of adapted scientific articles students had to read and the extent of their usage of the metacognitive tool. The set of guidelines for posing questions, which was part of the metacognitive tool, included three characteristics of posing a quality question: the thinking level required for answering the question, the number of chemistry understanding levels required for answering the question, and the contribution of the information needed for better understanding of the article.

The contributions of the two studies described in this chapter are the following: (a) The metacognitive tool, developed by the authors, was found to improve students' metacognition (both knowledge and regulation of cognition); (b) from a practical point of view, the ability to pose complex questions, assisted by metacognitive knowledge, is an important contribution for improving students' understanding of chemical phenomena and scientific research.

This chapter is unique in several aspects. First, it sheds light on the relationship between metacognition and the ability to pose questions in a case-based or adapted scientific article learning setting. Second, both studies are large scale and apply chemistry understanding levels. Third, each study involves a different complexity level of scientific articles adaptation. Finally, each study applies several research tools and learning settings of chemical education. This multidimensional setting provides a solid basis for concluding that the metacognitive tool developed as part of these studies is effective in fostering students' metacognition, their question posing skill, and the ability to reflect on their own reading strategies.

The metacognitive components in this chapter include: (a) knowledge of cognition – students' ability to identify the reading strategies they applied for understanding the adapted articles and to provide justifications for asking these questions based on the metacognitive tool and the chemistry understanding levels; (b) regulation of cognition – students reflected on the questions they had posed in order to plan in advance how to approach future question posing tasks. They evaluated the questions they had generated based on the taxonomy they had been taught, and rephrased their questions to be more complex – a regulation/control function.

In Chap. 9, "Explicit Teaching of Metastrategic Knowledge: Definitions, Students' Learning, and Teachers' Professional Development," Zohar presents an overview of a comprehensive research program in biology classrooms, covering six publications that investigated three different aspects of metastrategic knowledge (MSK), which is a subcomponent of metacognition: (a) a conceptual analysis of MSK;

(b) experiments examining the effects of explicit teaching of MSK; and (c) research about teachers' knowledge and professional development in the context of MSK. The conceptual analysis of MSK views this construct as general, conscious awareness of the thinking strategies applied during instruction and knowledge of their general characteristics, including knowledge about when, why, and how to use them. The chapter's main claim is that adding MSK to routine instruction of higher-order thinking in science classrooms has a substantial contribution to the development of students' thinking skills. The chapter then describes a series of three consecutive empirical studies that explored this claim. Study 1 explored the effects of explicit instruction of MSK concerning the control of variables thinking strategy on a small scale, tightly controlled, "laboratory-like" setting. Study 2 explored whether the effects were preserved in a larger scale study that took place in authentic classroom situations. Study 3 broadened the scope of the previous findings by exploring two additional thinking strategies: defining research questions and formulating hypotheses. The findings of all three studies showed a similar pattern: dramatic developments were obtained in students' strategic and metastrategic thinking following instruction. The effect of the treatment was preserved in delayed transfer tests. Explicit teaching of MSK had a particularly strong effect for low-achieving students. These findings show the significance of explicit teaching of MSK for teaching higher-order thinking skills in general and the significance of teaching it to low-achieving students in particular.

The final sections of this chapter report two additional studies concerning teachers' knowledge in the context of teaching MSK. These studies showed that teachers' initial metastrategic knowledge was lacking and insufficient for teaching purposes. Following professional development, considerable progress was made in teachers' knowledge of MSK and in their pedagogical abilities to use this knowledge in the classroom. These findings show that a professional development course can indeed help teachers make considerable progress with respect to the knowledge that is required for applying MSK in the classroom.

This chapter has two special features. The first feature is the replication of the research design of the small scale, tightly controlled, "laboratory-like" setting in a larger scale study that took place in authentic classrooms. The similar pattern of results in the two studies grants the findings extra credibility. The second feature is the attempt to cover learning and instruction of MSK from two angels, linking issues pertaining to students' MSK thinking to that of teachers.

In terms of metacognitive components, this study addresses MSK, which can be mapped to two components of metacognitive knowledge according to Flavell: knowledge about tasks (referring to task characteristics that call for the use of a strategy, or "when" to use a strategy) and knowledge about strategies (referring to "why" and "how" to use a strategy).

Chapter 10, "A Metacognitive Teaching Strategy for Preservice Teachers: Collaborative Diagnosis of Conceptual Understanding in Science," by Eldar, Eylon, and Ronen, is unique in terms of the population it targets – preservice elementary science teachers. The chapter is unique also in terms of its goal: using a preservice science course for developing not only prospective teachers' science content knowledge, but also their pedagogical content knowledge (PCK). This goal aims to

bridge the huge gap that traditionally exists in teacher preparation programs between the traditional way most content courses are taught and the innovative pedagogical strategies that are recommended to preservice teachers in their pedagogical courses. The instructional methodology the authors use to achieve this purpose is sophisticated: in terms of teaching the physics content, the course applies the Collaborative Diagnosis of Conception (CDC) strategy. CDC is a metacognitive strategy aimed at developing deep understanding of content in optics by helping learners to expose their prior conceptions and by giving them an opportunity to discuss and reconsider their ideas. In terms of teaching PCK, the course does two things: (a) it models a desired instructional strategy (i.e., the CDC strategy) that the preservice teachers experience as learners; and (b) it helps the preservice teachers become conscious of this instructional strategy by systematic metacognitive thinking about the learning processes. Metacognition is thus applied in this chapter twice, for two different purposes: First, the CDC strategy uses metacognition to improve physics content knowledge, and second, metacognition is used to scaffold preservice teachers' awareness of the instructional strategies that were used, thereby helping them construct their PCK.

The study reported in this chapter compares two different versions of the course. The implementation of the CDC strategy was the same in both versions, but they differed in the amount of metacognitive scaffolding for the pedagogical aspects of learning. The results indicate that the CDC strategy helped preservice teachers develop a high level of conceptual understanding that goes beyond the achievements in traditional courses. However, the findings also show that preservice teachers cannot extract the pedagogical knowledge to be learned from the course by themselves. Without the reflection on the structure and rationale of the teaching strategy, they did not realize the pedagogical elements of the strategy. These results suggest that it is possible to promote PCK in content courses, but the metacognitive support is necessary for this type of learning.

Finally, Chap. 11, "Toward Convergence of Critical Thinking, Metacognition, and Reflection: Illustrations from Natural and Social Sciences, Teacher Education, and Classroom Practice," by Ford and Yore, is unique in the sense that rather than examining the effects of metacognition or of any of its components, it aims to examine the relationships between metacognition and two other important constructs: critical thinking and reflection. These three constructs have recently become significant in education because the move toward constructivism requires more complex and sophisticated means for handling knowledge than had been required prior to the era of constructivism. The authors show how each of the three constructs grew out of a different discipline related to education: critical thinking grew out of philosophy, metacognition grew out of psychology, and reflection about practice grew out of progressive education, and the need to support instructional practice that would be responsive to divergent situations and variations in students' needs. The authors describe several studies they and others conducted in the context of each of the three constructs, documenting ambiguous definitions, overlapping components of these constructs and fuzziness in terms of the relationships among the three constructs. The chapter concludes by offering a model of convergence, arguing that an

integrated view of the three constructs is potentially more powerful than treating each of the constructs separately in meeting the complex cognitive demands of high-quality education in the domains of science and social science.

The significance of this chapter in the context of the other chapters in this book is in extending the conceptual discussion on metacognition. The chapter shows that the "fuzziness" of the definitions in the area of metacognition is limited neither to the "fuzzy borders" between metacognition and cognition, nor to the "fuzzy borders" between the various functions of metacognition. The "fuzziness" extends also to the "fuzzy borders" that exist between metacognition and other important constructs in the field of thinking and learning. Ford and Yore's main contributions are: (a) in pointing out this extension, (b) in taking an important step toward clarifying what is unique to each of these concepts, and (c) in pointing out that these three constructs have potential areas of convergence. The convergence, they claim, is potentially more powerful for learning and instruction than when each of these constructs stands alone. Therefore, it makes sense to continue investigating this convergence and its potential significance.

General Comments

Examining the chapters in this book collectively, we make several general comments. First, it is interesting to note that in all the eight research-based chapters, the study of metacognition was not an end to itself. Rather, it was integrated into a study of the role and significance of other central and important constructs, such as self-regulation, the CDC strategy, literacy, teaching thinking strategies, motivation, and conceptual understanding. This may be taken as a sign of the maturity and prominence of metacognitive research within the discipline of science education, pointing to the deep penetration of metacognition into central research agendas that researchers in the field currently undertake. It seems that the growing recognition of the potential value of metacognition for science learning increasingly motivates researchers in different areas of science education to incorporate this construct into their ongoing research.

Second, two of the chapters (9 and 10), address pre- and in-service teachers' learning. Together with recent studies on the role of metacognition in teacher learning, which are not represented in this book (e.g., Abd-El-Khalicka and Akerson 2009), this trend indicates that science educators are beginning to experiment with ways for addressing questions pertaining to the pedagogical aspects of using metacognition in the classroom. In order to do this, teachers need to have a sound knowledge of metacognition itself, as well as a sound pedagogical knowledge of how to use metacognition during instruction (see Chap. 9). Sound teachers' knowledge of these two elements is necessary for large-scale implementation of metacognition in science classrooms. It is therefore crucial that in the near future, these two elements will become a more dominant focus of research in science education. Such research

will serve as a preparation for incorporating metacognition as a salient component in preservice and in-service teachers' courses.

Third, the study of thinking strategies in the context of science education and the study of conceptual knowledge are unfortunately conducted too often as two distinct research agendas that are totally disconnected. In contrast, six of the Chaps. (4–8, and 10) address relationships between metacognition, i.e., thinking about thinking, and science content knowledge, or conceptual understanding. This supports the statement made earlier about the need for specialized studies of metacognition with common and distinct features in diverse content areas. Integrating metacognition into science education thus also indicates that metacognition is indeed becoming a significant factor in the design of innovative ways to promote students' subject-matter knowledge in science classrooms.

Toward an Integrated View of the Various "Metacognitions" in This Book

Finally, let us examine the chapters in this book from the perspective of an integrated view of metacognition. The "fuzziness" in the definitions of metacognition (see pages 2, 11 and 12 above) makes it difficult to discuss several studies together in an integrated and clear way. Sometimes a clear conceptual statement is absent in empirical studies in this area, but even when it does exist, it is not easy to achieve a coherent overview. As noted, the theoreticians in the general field of metacognition cited by our science education authors endorse different theoretical perspectives. Some of these perspectives reflect the prevalent "fuzziness" in the field. Others may be internally clear, but are still not clear in how the various perspectives relate to each other. Since different researchers mean different things by using the same term (i.e., metacognition, or some of its components), we often cannot determine which component(s) of this complicated concept they are in fact applying in their study, what their exact view of these components is, and how the findings from various studies relate to each other.

A major goal of this book is to address this issue. A coherent and comprehensive conceptual analysis of the field is beyond the scope of this book. Nevertheless, we believe that one of the contributions of this book is the attempt to reduce the ambiguity that so often exists in this area. This is carried out by two means. First, the author(s) of each chapter were asked to define their perception of metacognition in a clear way, and to state explicitly how their research addresses that definition. Consequently, each of the chapters indeed states, based on the literature, just what the author(s) mean by addressing metacognition in their research. As editors, we engaged authors in an iterative process of refining these statements toward a more cohesive body of chapters. Although this process comes at the price of chapters repeating each other in citing several identical references, we believe that our persistence paid off, as each of the chapters pays considerable attention to this critical issue.

Second, the explicit statement in each chapter concerning its theoretical underpinning allowed us to provide a more integrated view of the various metacognitive components applied throughout the book and their interrelationships with science learning. An explicit and clear statement defining the meaning of metacognition and some of its components in each chapter is clearly a necessary step in the effort to construct a coherent, integrated picture of research in this area. It is, however, not a sufficient step.

The fact that the chapters are based on different theoretical frameworks made this analytical process quite difficult, because it requires a comparison between various views of metacognition that may not have too much in common. We addressed this problem by choosing one theoretical framework against which we mapped the various chapters. After much deliberation and consultation of the literature, we decided to choose the framework formulated by Flavell et al. (2002, pages 153, 154, 170, 171), with slight adaptations. The reasons for choosing this particular framework are the following: (a) Flavell is a leading figure in research on metacognition, and his definition is a prominent one which served as the foundation for many subsequent frameworks. Therefore, even if the full, more current framework diverged from that definition in some of its points, it still provided a common ground for our mapping process; and (b) this framework is rather simple and clear, yet it addresses many (even if not all) of the metacognitive components that appear in other frameworks.

As several of the chapters explain, central to the definition of Flavell et al. (2002) is the distinction between *metacognitive knowledge*, and *metacognitive monitoring and self-regulation*. Metacognitive knowledge includes three sub-categories: *knowledge about persons, tasks, and strategies*. The persons category includes any knowledge and belief a person might have concerning what human beings are like as cognitive processors, including knowledge of one's own cognitive characteristics, knowledge about cognitive differences between people, and knowledge about cognitive similarities among all people, i.e., about universal properties of human cognition. The *task* category has two subcategories. One has to do with the nature of the information one encounters and deals with in any cognitive task, while the other concerns the nature of the task demands. The *strategy* category includes knowledge about what means or strategies are likely to succeed in achieving what cognitive goals. Flavell et al. also note that the bulk of a person's metacognitive knowledge actually concerns combinations of, or interactions among, two or three of these categories.

While Flavell et al. (2002) have mentioned *metacognitive monitoring and self-regulation* explicitly when referring to the components of metacognition, they also bring up "planning" and "evaluating" through use of relevant examples (see Flavell et al. 2002, pages 150 and 153). Since these concepts appear in so many of the other frameworks of metacognition in the literature in general and in this book in particular, and since they are mentioned in the examples depicted by Flavell et al. (2002), our analysis includes these terms explicitly (see Table 1.1). *Metacognitive monitoring and self-regulation* thus include activities of *planning*, *monitoring,*

Table 1.1 Mapping the various authors' definitions of metacognition in research-based chapters against the definition of Flavell et al. (2002)

	Metacognitive knowledge			*Metacognitive monitoring and self-regulation*			
Flavell et al. (2002)	Knowledge of persons	Knowledge of tasks	Knowledge of strategies	Planning	Monitoring	Evaluating	Self-regulating/(controlling)
Chapter 3: Norris and Phillips					+		+
Chapter 4: Schraw et al.	Knowledge of cognition			Regulation of cognition			
Chapter 5: *Grotzer*	+				+	+	
Chapter 6: Whitebread and Grau				+	+		+
Chapter 7: Chiu and Linn	+				+	+	+
Chapter 8: Herscovitz et al.			+	+	+	+	+
Chapter 9: Zohar		+	+				
Chapter 10: Eldar et al.	+	+	+	+	+		+

and *evaluating* one's cognitive activities, and finally, giving instructions for further cognitive activities, i.e., *self-regulating* one's cognition.

Flavell and his colleagues also wrote about metacognitive experiences, which are not discussed in our analysis since they address meta-level affective experiences, while our discourse is limited to meta-level cognitive experiences.

Table 1.1 maps the various authors' definitions of metacognition in the research-based chapters of this book against the definition of Flavell et al. (2002). Our interpretation of Flavell et al.'s definition of metacognition appears in the top lines of Table 1.1. It includes *metacognitive* k*nowledge* and *metacognitive monitoring and self-regulation* as two main categories. Knowledge of cognition is further divided into knowledge of *persons, tasks,* and *strategies*. Metacognitive monitoring and self-regulation of cognition is further divided into *planning, monitoring*, *evaluating,* and *self-regulating/controlling*.

We analyzed the metacognitive components applied in each chapter according to these categories. Since we map the authors' definitions against the specific definition of Flavell et al., which is not necessarily the definition adopted by each chapter's author, this process sometimes required interpretation. Since interpretations are subjective and may be prone to differing views, we summarize below the authors' definition in their own words. When necessary, we explain why we interpreted their work the way we did (see Table 1.1).

Norris and Phillips (Chap. 3) discuss reading metacognition that includes "the monitoring and control (jointly the regulation) of thinking while reading." In their chapter, they focus on two types of metacognitive judgments made by students reading scientific texts: judgments about the difficulty of the text, and judgments about the effect of what they have read on prior beliefs. The authors explain that both these judgments relate to the monitoring function of metacognition. These judgments can affect how readers subsequently control their reading. Accordingly, metacognition in this chapter refers to two of the categories in Table 1.1: monitoring and self-regulating/controlling.

Schraw and his colleagues (Chap. 4) state that the Jr. MAI instrument they used in their study assessed students' knowledge and regulation of cognition. However, because the authors' (very clear) definition of metacognition is different than the one used by Flavell et al., it was difficult to align the two definitions on the level of the subcategories without distorting the authors' meaning. For the purposes of Table 1.1, we therefore preferred to keep the more general categories of knowledge and regulation of cognition rather than to make more detailed classifications pertaining to the subcategories.

The metacognitive components addressed by Grotzer and Mittlefehldt (Chap. 5) are also defined by using frameworks that are quite distinct from the one used by Flavell and his colleagues. While some of the metacognitive components discussed in Chap. 5 match the components of Table 1.1 directly, others do not. Knowledge of persons, monitoring, and evaluation appear both in the chapter and in Table 1.1. However, awareness and self-reflection that have a prominent role in the chapter have no parallel category in the table.

The research presented by Whitebread and Grau (Chap. 6) states that metacognitive knowledge was not frequently observed by itself within the data collected, as the predominant type of behavior observed was of online regulation, namely, planning, monitoring, control, and reflection. We therefore inserted the first three categories into Table 1.1. However, since Table 1.1 does not have an appropriate category, reflection is not represented in it. The table also does not capture additional facets of Whitebread and Grau's view of metacognition, such as overlapping areas and interrelationships among subcomponents of metacognition as well as its relationships with other important constructs.

In Chap. 7 by Chiu and Linn, metacognition involves some form of self-knowledge and of self-regulation. The knowledge about oneself as a learner, such as knowing what you know or do not know, matches the table's category of "knowledge of persons." In terms of self-regulation, it seems that "monitoring" and "evaluating" in the chapter match the same categories as those in Table 1.1. Revisiting one's activities may be interpreted as a form of the category "regulating/controlling" in Table 1.1.

Chapter 8, by Herscovitz et al., refers to students' ability to identify the strategies they applied and to provide justifications for asking the questions they had posed. This component matches the "knowledge of strategies" component in Table 1.1. In addition, the chapter addresses four components of regulation of cognition: planning in advance how to approach future question posing tasks; monitoring and evaluating the questions students generated based on the taxonomy they had been taught; and regulating/controlling future questions posing processes.

In Chap. 9, Zohar explains metastrategic knowledge (MSK) according to the definitions of several researchers, one of whom is Flavell and colleagues. Therefore, this construct easily matches two components of metacognitive knowledge according to Flavell: knowledge about tasks (referring to task characteristics that call for the use of a strategy, or "when" to use a strategy) and knowledge about strategies (referring to "why" and "how" to use a strategy).

In Chap. 10, Eldar et al. apply metacognition for two different purposes. First, metacognition is used in teaching preservice students to understand physics subject matter knowledge. Second, it is used for the purpose of helping the preservice teachers construct their pedagogical content knowledge. The authors' detailed view of metacognition is presented in the first figure of their chapter. Some of their categories match the categories in Table 1.1. In this chapter, metacognitive regulation is viewed as consisting of monitoring, planning, and control. These have matching categories in Table 1.1, but learner autonomy does not have a matching category. Metacognitive knowledge is viewed as consisting of knowledge about people (both knowledge about how I think and knowledge about how others think), strategies, and tasks that match categories in Table 1.1. It also consists of an additional category, knowledge about knowledge integration, further divided into knowledge of optics and knowledge of pedagogy, which is unique to this chapter and has no matching category in Table 1.1.

Examination of the data presented in Table 1.1 shows that five of the eight research-based chapters address both knowledge and regulation of cognition, confirming that the strong interrelationships between these two metacognitive

dimensions are indeed salient features of research on metacognition in science education. Knowledge of persons is applied in three chapters, knowledge of tasks in two chapters, knowledge of strategies in three chapters, planning in three chapters, evaluating in three chapters, and self-regulating/controlling in five chapters.

Table 1.1 also shows that monitoring is found in six of the eight chapters. Although we did not perform a subdivision of the metacognitive view in Chap. 4, a close look at the Jr. MAI instrument used in that chapter shows that monitoring is also addressed in Chap. 4. We can therefore conclude that monitoring one's thinking and understanding is the most prevalent category of metacognition applied in the science education research presented in this book. Further research is required to establish whether this conclusion can be generalized to other studies in science education.

A close look into several of the chapters reveals some form of general, meta-level knowledge constructs. In Chaps. 8–10, these meta-level structures were classified in Table 1.1 into the "knowledge of strategies" subcategory. However, knowledge of strategies covers only some of the meta-level constructs that appear throughout the book. In Chap. 3, Norris and Phillips write about a normative view of reading, i.e., a view of the goals of reading and what counts as good reading. This view may be seen as a form of meta-level belief and knowledge about what reading actually is. In Chap. 5, Grotzer and Mittlefehdlt focus on meta-structural knowledge about causality, i.e., the ability to reflect upon and recognize particular forms of causal patterns. In Chap. 10, in addition to knowledge of strategies, Eldar et al. present two additional meta-level knowledge constructs: one about the knowledge integration strategy in terms of optics and the other in terms of pedagogy. Meta-level knowledge constructs thus appear to be quite prevalent in these chapters and indeed go beyond the knowledge of strategies. The reality of such meta-level knowledge constructs therefore seems to be a recurrent pattern in science learning in different domains and may thus have substantial implications for science learning. Future research should look into these constructs in order to find out more about their common characteristics and about their potential applications in the classroom.

One component that was addressed in several chapters but is not included in Table 1.1 is reflection. The chapter by Yore and Ford views reflection and metacognition as two distinct concepts with an overlapping area. The recurrent use of reflection as part of metacognitive thinking in the chapters of this book calls for another look at this issue in order to consider the role of reflection in the metacognitive processes described in the various chapters.

Suggestion for Future Research

Our attempt to provide an integrated view of the various metacognitive components applied throughout the book should be viewed as a first step in this direction. The effort to align the definitions of all the chapters with the definition of Flavell and his colleagues captured most of the metacognitive elements addressed by

the chapters, but not all of them. This indicates the richness of current research that extends well beyond the prominent definition formulated by Flavell and his colleagues a decade ago. Nevertheless, we believe that striving for more clarity and uniformity in metacognition research is crucial for the field because only commonly accepted definitions would enable us to understand exactly what was studied in each research, to look at studies in an integrated way, and to draw general conclusions across studies. We suggest that clear definitions of the metacognitive component(s) addressed in new studies would become a normative standard requirement for research in this field. Moreover, we call for a collaborative endeavor to continue our initial work and take it a step forward toward common grounds and standard definitions in the domain of metacognitive research.

We are looking forward to future research centering on a process whose goal would be the formulation of a definition that: (a) will attend to the rich and varied elements that appear in the literature by creating a comprehensive analysis and integration, and (b) will be accepted by at least a group of prominent researchers in the field. Rather than being the work of one or two persons, such an endeavor requires team work: a group of experts that will collaborate in creating consensus regarding a consistent and complete set of related definitions. These definitions will take into account as many of the varied facets that appear in the literature as possible. The expert group would need to interpret the definitions found in the literature, redefine various metacognitive elements, incorporate new elements generated by current studies into the definitions, show the interrelationships among various elements, and define interrelationships between metacognition and other close concepts (including reflection, critical thinking, and self-regulated learning). The production of a conceptual framework that will have consensus among a group of prominent scholars will allow future researchers to use it as the foundation for their investigations. They will no longer need to explain in detail according to which view they are working. Instead, they will only need to explain which parts of that definition they adopt. In the case of deviation from that definition, they will have to explain carefully exactly in which points they diverge from it. Such a process will allow more clarity and a more profound integration across various research projects than is currently possible.

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Chapter 2
Metacognition in Science Education: Definitions, Constituents, and Their Intricate Relation with Cognition

Marcel V.J. Veenman

Introduction

One of the reappearing problems with metacognition research is the "fuzziness" of the concept and its constituents. This fuzziness is not only due to a proliferation of terminologies. Researchers also disagree about the ingredients of metacognition and their interrelationships (Veenman et al. 2006). In the literature on metacognition, starting with Flavell (1976, 1979) and Brown (1978), a distinction is often made between metacognitive knowledge and skills (Schraw and Moshman 1995; Veenman et al. 2006). The latter is sometimes referred to as executive or self-regulatory processes (Kluwe 1987; Winne 1996; Zimmerman 1995).

Apart from the distinction between metacognitive knowledge and skills, also a difference in the pace of developmental processes has been found. Metacognitive-knowledge development commences at the age of 6 years and continues thereafter (Berk 2003). Although elementary forms of planning and self-correction have been observed in playful situations with 3–5-year-old children (Whitebread et al. 2009), it is generally acknowledged that the development of "academic" metacognitive skills in formal learning situations arises at the age of 8–10 years (Berk 2003; Veenman et al. 2006). A steep linear development of metacognitive skills occurs during the secondary-school years (Veenman et al. 2004).

This chapter addresses the various components of metacognition and their interrelations. In particular, a comprehensive theory on the nature and origin of metacognitive skills will be presented. Finally, it will be shown how metacognitive skills enter the arena of science education.

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Metacognitive Knowledge

Metacognitive knowledge refers to one's declarative knowledge about the interplay between person, task, and strategy characteristics (Flavell 1979). For instance, a learner may think that s/he (person characteristic) is not proficient in math (task characteristic) and, therefore, that s/he should invest a lot of effort in making homework assignments (strategy characteristic). Though some researchers implicitly assume that metacognitive knowledge only refers to correct knowledge (e.g., Schraw and Moshman 1995; Simons 1996), it is maintained here that metacognitive knowledge can be either correct or incorrect. Learners may underestimate or overestimate their competences. Moreover, metacognitive knowledge does not guarantee an adequate execution of appropriate strategies, as the leaner may lack motivation or capability. Consequently, metacognitive knowledge often poorly predicts learning outcomes (Veenman 2005). A good deal of metacognitive knowledge has its roots in a person's belief system, which contains broad, often tacit ideas about the nature and functioning of the cognitive system (Flavell 1979). Beliefs are personal and subjective by nature.

Since researchers embarked on the study of metacognition in the 1970s of the last century, several subcomponents of metacognitive knowledge have been identified. The first component under study was metamemory (Flavell 1970; Flavell and Wellman 1977). Initially, metamemory only referred to the declarative knowledge about one's memory capabilities and about strategies that affect memory processes (Cavanaugh and Perlmutter 1982). It was assumed that this factual knowledge of memory processes would affect memory performance. Later on, especially within the study of Feeling of Knowing (FOK) and Judgement of Learning (JOL), the focus of metamemory research shifted from the knowledge product of metamemory to the process of metamemory (Nelson and Narens 1990). Both FOK and JOL refer to a person's predictions about future test performance, either on items that are known (JOL), or on items that are not yet mastered (FOK). This process approach to metamemory stresses the role of monitoring or evaluation of memory contents. By including monitoring activities, metamemory research has crossed the borderline between metacognitive knowledge and skills. Consequently, metacognitive knowledge about the memory system and monitoring skills for evaluating memory cannot be disentangled in the prediction of actual memory performance. Recent metamemory research, however, did account for the missing link between Theory of Mind (TOM) and metamemory as a starting point of metacognitive development (Bartsch and Estes 1996; Lockl and Schneider 2006). TOM pertains to children's knowledge about the mind and, in particular, the understanding of a 5-year-old child that another person may not know what the child knows (Flavell 2004). Longitudinal studies of Lockl and Schneider have shown that TOM at the age of 4–5 years is a precursor of later metamemory performance. Apparently, the development of metacognition has its roots in earlier cognitive development.

Another component of metacognitive knowledge is conditional knowledge (Schraw and Moshman 1995). Conditional knowledge pertains to declarative knowledge about when a certain metacognitive strategy should be applied and to

what purpose. Poor learners often do not know what strategy to choose, why they should use that strategy, and when to deploy that strategy. Even adequate conditional knowledge, however, does not guarantee the actual execution of a strategy as a learner may still miss the procedural knowledge for how the strategy should be enacted. In fact, conditional knowledge provides an entry to the first stage of skill acquisition, where a metacognitive strategy has to be consciously applied step-by-step and gradually transformed into a skill through proceduralization (see below; Alexander and Jetton 2000; Anderson and Schunn 2000). Thus, conditional knowledge is a prerequisite, but not sufficient condition for the acquisition of metacognitive skills. This is one of the reasons why Kuhn (1999) and Zohar and Ben David (2008, 2009) postulated the notion of metastrategic knowledge, which encompasses both conditional knowledge and procedural knowledge for how to use a strategy.

Acquisition of Metacognitive Knowledge

Where does metacognitive knowledge come from? It was outlined before that the belief system, which contains naïve theories and tacit ideas about cognitive functioning, provides a source of information from which metacognitive knowledge is built. Other information sources are judgments and feedback from other people, and metacognitive experiences (Flavell 1979; Efklides 2006). Metacognitive experiences have in common with metacognitive knowledge that both originate from a monitoring process. Metacognitive knowledge, however, refers to memory-retrieved knowledge, whereas metacognitive experiences concern on-line feelings, judgments, estimates, and thoughts that people become aware of during task performance. According to Efklides, metacognitive experiences are nonanalytic, nonconscious inferential processes that are driven by affective experiences, such as liking, interest, curiosity, disappointment, and being startled. Hence, metacognitive experiences are subjective by nature. For instance, while a task may have an externally defined objective level of difficulty or cognitive load (Sweller 1994), feeling of difficulty is determined by subjective estimates of task difficulty, which depend on person characteristics, such as cognitive ability, and affective factors, such as mood, among others (Efklides 2006). Metacognitive experiences may affect task performance directly through time on task and effort expenditure. Although metacognitive experiences arise from unconscious inferential processes during task performance, as soon as learners become consciously aware of them, they may feed into the cognitive system and "freeze" up to relatively stable metacognitive knowledge.

Assessment of Metacognitive Knowledge

Metacognitive knowledge is usually assessed through either prospectively or retrospectively administered questionnaires, through item-by-item evaluations, or through retrospective interviews. These self-report instruments inherently pose

some validity problems (Veenman 2005). They run the risk of provoking socially desirable answers, especially in case questions inquire after specified knowledge. They may not reflect the knowledge that is actually used *during* task performance. Finally, learners may use individually different reference points and standards for replying to questions with closed answers, thus enhancing internal consistency but reducing validity at the same time (Veenman et al. 2003). FOK and JOL measures are least affected by these validity problems, as they require the individual to subjectively estimate the understanding and reproducibility of memory items.

Metacognitive Skills

Metacognitive skills pertain to the acquired ability of monitoring, guiding, steering, and controlling one's learning and problem-solving behavior. There is some consensus of what learning activities are typical for metacognitive skills. The overview presented here is by no means exhaustive. For instance, Pressley and Afflerbach (1995) distinguished some 150 different activities in detail for reading, while Meijer et al. (2006) drew up a list of 65 activities for solving physics problems. This chapter, however, merely presents a global description of what kind of activities are regarded as being representative of metacognitive skills. Quite often, a distinction is made between activities at the onset of task performance, during task performance, and at the end of task performance. At the onset of task performance, one may find activities, such as reading and analyzing the task assignment, activating prior knowledge, goal setting, and planning. These activities are preparatory to actual task performance. Indicators of metacognitive skillfulness during task performance are systematically following a plan or deliberately changing that plan, monitoring and checking, note-taking, and time and resource management. These activities guide and control the execution of the task at hand. At the end of task performance, activities such as evaluating performance against the goal, recapitulating, and reflection on the learning process may be observed. The function of these activities is to evaluate and interpret the outcome, and to learn from one's course of action for future occasions.

At first glance, the metacognitive activities of learners may vary from task to task and from one domain to another (Kelemen et al. 2000; Glaser et al. 1992). For instance, orienting activities for text studying include reading the title and subheadings, scanning the text to get an overview, activating prior knowledge, goal setting for reading, and getting hold of test expectations. Orientation during problem-solving encompasses reading the problem statement, activating prior knowledge, goal setting, making a drawing representing the problem, establishing what is given and what is asked for, and predicting a plausible outcome. Similarly, planning in reading looks different from planning while solving physics problems. When studying a text, planning activities concern decisions about what to read first and how to navigate through the text. Planning in problem-solving pertains to the design of a step-by-step action plan of problem-solving activities. Although specific overt activities are

evoked by different learning tasks, these activities spring from similar metacognitive grounds. If you have the same person performing a reading task and a problem-solving task, then orientation, planning, and other metacognitive activities for both tasks appear to have much in common, even though they superficially look different (Van der Stel and Veenman 2008). There is ample evidence that metacognitive activities, or the metacognitive skills they emanate from, appear to be domain surpassing or general by nature, rather than domain specific (Schraw et al. 1995; Schraw and Nietfeld 1998; Veenman et al. 1997, 2004; Veenman and Verheij 2003). Apparently, students have a personal repertoire of metacognitive skills that they tend to apply whenever they encounter a new learning task. This notion of general metacognitive skills has implications for the training and transfer of those skills across tasks and domains.

Metacognitive Skills and Cognitive Processing

Incidentally, students clearly express their intention to apply a metacognitive skill, which by no means is a guarantee that they are capable of adequately doing so. Most of the time, however, metacognitive skills remain covert mechanisms that take place inside the head (Veenman et al. 2006). Consequently, these metacognitive skills cannot be directly assessed, but have to be inferred from their behavioral consequences (Veenman 2007). For instance, when a student spontaneously recalculates the outcome of a problem, it is assumed that a monitoring or evaluation process must have preceded this overt cognitive activity.

A perennial issue, then, is that higher-order metacognitive skills heavily draw on lower-order cognitive processes (Brown 1987; Slife et al. 1985). A few examples may elucidate this tight connection between metacognitive and cognitive processes: Analysis of the assignment requires reading and reasoning processes; activating prior knowledge is driven by memory processes; planning involves processes of serialization and sequencing; comprehension monitoring while reading relies on vocabulary and other verbal processes; checking the outcome of a calculation requires numerical processes; note-taking depends on writing processes; drawing conclusions entails inferential reasoning; both evaluation and reflection imply cognitive processes of making comparisons. Metaphorically speaking, metacognitive skills represent the driver, while cognitive processes form the vehicle for employing those metacognitive skills.

The problem of disentangling higher-order from lower-order skills is deeply rooted in psychological theory of human consciousness. Conceptualizations of metacognition have in common that they take the perspective of "higher-order cognition about cognition" (Flavell 1979; Nelson 1999). These conceptualizations stress the supervisory role of metacognition in the initiation of and control over cognitive processes. A higher-order agent is overlooking and governing the cognitive system, while simultaneously being part of it. This is the classical homunculus

problem (Elshout 1996), otherwise referred to as Comte's paradox (Nelson 1996). One cannot split one's self into two, of whom one thinks while the other observes him thinking. What then is the higher-order nature of metacognitive skills?

Metacognitive Skills as Self-instructions

Nelson (1996; Nelson and Narens 1990) gave an initial impetus to a unified theory of metacognition. Basically, he distinguished an "object level," at which level cognitive activity takes place, from a "meta-level" which governs the object level. Two general flows of information between both levels are postulated. Information about the state of the object level is conveyed to the meta-level through monitoring processes, while instructions from the meta-level are transmitted to the object level through control processes. Thus, if errors occur on the object level, monitoring processes will give notice of it to the meta-level and control processes will be activated to resolve the problem. This seems an elegant model, including both metacognitive skills for monitoring and controlling cognitive activity and metacognitive knowledge as the result of monitoring processes.

According to Nelson's model, metacognition can be seen as a *bottom-up* process, where anomalies in task performance trigger monitoring activities, which in turn activate control processes on the meta-level. A limitation of this bottom-up model is that it does not clarify how monitoring processes themselves are triggered (Dunlosky 1998). Moreover, the model does not account for spontaneous activation of control processes without prior monitoring activities, thus neglecting the goal directedness of problem-solving and learning behavior (Prins 2002). As an extension to Nelson's model, metacognition could also take the perspective of a *top-down* process of self-instructions for the regulation of task performance (Veenman 2011). Apart from being triggered by task errors, the latter top-down process can also be activated as an acquired program of self-instructions whenever the learner is faced with task performance. This program of self-instructions could be represented by a production system of condition-action rules (Anderson 1996; Butler and Winne 1995; Schunn and Anderson 1999):

IF you encounter a task, THEN look for the task assignment and take notice of it;
IF you have an idea about the task assignment, THEN try to dig up from memory as much as you know about the subject matter;
IF you understand the task assignment, THEN formulate the goal to be achieved;
IF you have set your goal, THEN design an action plan for attaining that goal;
IF you have an action plan, THEN follow that plan in a systematical way;
IF you are executing your action plan, THEN keep a close watch on what you are doing and detect any anomalies;
Etc.

This production system embodies a set of self-induced metacognitive instructions to the cognitive system. Thus, quite in line with Nelson's model, self-instructions

from the meta-level evoke various cognitive activities at the object level. The resulting cognitive activities can be very general (e.g., sorting out relevant information), or rather specific (e.g., looking for particular keywords that point to a certain theory), depending on the available prior knowledge.

How do humans acquire such a production system of metacognitive self-instructions? According to ACT theory (Anderson 1996; Anderson et al. 1997), skill acquisition passes through three successive stages. In the cognitive stage, declarative knowledge of condition and actions is interpreted and arranged in order to allow for a verbal description of a procedure (What to do, When, Why, and How; Veenman et al. 2006). The execution of the procedure progresses slowly because all activity needs to be consciously performed step-by-step. During the acquisition of metacognitive skills at this stage, metacognitive knowledge, in particular conditional knowledge, is incorporated in a verbal description of the procedure. In fact, conditional knowledge contains information about the "Why" and "When" (Schraw et al. 2006), defining the IF-side of a production rule. The "What" and "How" constitute the THEN-side of a production rule. The conscious execution of the procedure at this stage explains why the initial acquisition of metacognitive skills through instruction or training requires extra effort, which may even interfere with cognitive performance (Veenman et al. 2006). In the second, associative stage, verbal descriptions of the procedure are transformed into a procedural representation through "compilation." Errors in the procedure are eliminated, separate procedures are assembled into an organized set through composition, and references to declarative knowledge are removed through proceduralization. Consequently, the execution of procedures becomes faster and more accurate, requiring less effort. Finally, in the autonomous stage, the execution of productions is fine-tuned and automated. Many metacognitive skills will never reach this stage, as they need to be consciously applied and tuned to the task at hand (Nelson 1996). Monitoring processes, however, may run in the background until an error or anomaly is detected (Brown 1987; Butler and Winne 1995; Reder and Schunn 1996). In the same vein, elements of the planning process may become automated, thus requiring less deliberate and conscious activity until an obstacle prevents a plan from being executed (Pressley et al. 1989). At this point of automation, metacognitive knowledge is still available for reflection on the executed metacognitive skills afterwards.

It is important to acknowledge that both the metacognitive self-instructions and the cognitive processes that are involved in the execution of those instructions are part of the same cognitive system. Metacognitive and cognitive activities, however, serve different goals and functions within the cognitive system (Brown 1987; Butler 1998; Veenman et al. 1992). Cognitive activities are needed for the *execution* of task-related processes on the object level, whereas metacognitive activity represents the *executive* function on the meta-level for regulating cognitive activity. Thus, metacognitive self-instructions are much like a General who cannot win a war without cognitive soldiers. On the other hand, an unorganized army will neither succeed. It is my experience from studying many thinking-aloud protocols that successful learners easily shift from a cognitive performance mode to a metacognitive self-instruction mode, and vice versa.

It should be noted, though, that the self-instruction theory of metacognitive skills outlined above diverges from notions of metastrategic knowledge, also referred to as procedural meta-knowing (Kuhn 1999; Zohar and Ben David 2009; see also the Chap. 9). More specifically, one of the differences is that in the notion of metastrategic knowledge, planning activities are conceived as cognitive activities rather than metacognitive ones (Zohar and Ben David 2009). In the self-instruction theory of metacognitive skills, however, planning activities are considered to operate on the meta-level, while inducing cognitive activity on the lower-order object level (Veenman et al. 2006).

Assessment of Metacognitive Skills

In the assessment of metacognitive skills, a distinction is made between on-line and off-line methods (Veenman 2005). On-line methods refer to assessments during actual task performance, such as observation, thinking aloud, and computer log-file registration. Off-line methods, on the other hand, pertain to questionnaires and interviews that are administered either prior or retrospective to task performance. The questions in off-line methods inquire after the (frequency of) strategy use and skill application of a learner. The essential difference between on-line and off-line method is that off-line measures rely on self-reports from the learner him/herself, whereas on-line measures are obtained from judges, external to the learning process. Off-line self-reports suffer from the same validity problems as those for the assessment of metacognitive knowledge. Moreover, off-line measures hardly correspond to on-line measures (Hadwin et al. 2007; Veenman 2005, 2011; Veenman et al. 2003). Apparently, people don't do what they say they will do, nor do they recollect accurately what they have done. For these reasons, on-line methods should be preferred over off-line methods when assessing metacognitive skills.

Metacognitive Skills in Science Education

Science learning draws on many different cognitive processes, such as those involved in reading text, problem-solving, inquiry learning, and writing. When taking courses in physics, chemistry, or biology, students have to read text books in order to acquire conceptual understanding, they must learn to solve problems through reasoning and applying formula, they have to design, plan and carry out lab experiments, and they have to write reports or papers. For each of these basic activities in science learning, the most salient features of metacognitive behavior are depicted below.

Although much is known about metacognitive processes in reading and studying expository texts (Alexander and Jetton 2000; Alexander et al. 1991; Israel et al. 2005; Pressley and Afflerbach 1995; Schellings et al. 2006; Veenman and Beishuizen 2004; Walczyk 1994), relatively little is known about metacognitive processes in

science reading (Azevedo et al. 2007; Koch 2001; Meijer et al. 2006). The general picture of poor readers is that they tend to skip the title and paragraph headings, to refrain from setting goals and selecting reading strategies accordingly, to read linearly without noticing lack of comprehension, and to terminate reading without evaluation or reflection. Typically, after reading the last line of the text, they say "ready" as they think the chore is done. Proficient readers, on the other hand, start with orienting reading in order to grasp the theme or gist of the text. They read the title and paragraph headings, they skim through the text, and they purposefully read the concluding paragraph, while activating prior knowledge of the subject matter. They set reading goals and plans, depending on the nature of the text and on test expectations (e.g., answering multiple-choice or open-ended questions, or writing an essay). While reading, they monitor their comprehension, both on the level of individual words, as well as on the level of paragraphs or the entire text. They generate and answer questions about the text, through which they become more aware of what they know and do not know (Kaberman and Dori 2009; Veenman 2006). When they come across an unknown word, they either try to infer the word's meaning from its context or they deliberately navigate through the text in search for the meaning of the word. They make orderly notes and they keep track of time. After reading, they evaluate whether the reading goal is reached, they recapitulate the main ideas, and they comment on their own reading process. Research by Meijer et al. (2006) has shown that this distinction between poor vs. proficient readers is equally applicable to reading a physics textbook.

Learning to solve problems in science domains is often referred to as learning by doing (Elshout 1987). Research on the role of metacognition in science problem-solving is mainly restricted to the domain of physics and, in particular, to the comparison of novices vs. experts (Elshout et al. 1993; Glaser and Chi 1988; Mettes et al. 1981). Before taking action, physics experts carry out an extensive qualitative analysis of the problem statement, thereby generating an adequate problem representation (De Jong and Ferguson-Hessler 1984; Elio and Scharf 1990; Elshout 1987; Ertmer and Newby 1996; Larkin et al. 1980). After thorough orientation, experts design a detailed action plan, containing goals and directions for subsequent problem-solving activities (Elshout et al. 1993). Experts have more self-knowledge and stronger self-monitoring skills at their disposal (Glaser and Chi 1988). Conversely, novices in physics are characterized by a superficial problem analysis and a lack of other orientation activities. According to Elshout (1987), poor novices tend to search immediately for a formula that superficially matches with the data in the problem statement. Even when offered the opportunity to choose for specific help, they tend to skip orientation support and straight away ask for the correct formula with its computations (Elshout et al. 1993). They try to execute all problem-solving activities in one super-operation, including algebraic manipulations, substitution of numerical data into variable slots, and mental calculations. Furthermore, they virtually refrain from note-taking. By doing so, they often get stuck and they lose track of their problem-solving activities, which results in a disorderly pattern of memory traces. This muddling though of novices obstructs monitoring and evaluation processes. When an error is detected, one can hardly retrace the origin of the error.

Elshout (1987) referred to this pattern of metacognitive malfunctioning as the "novice syndrome." Not all novices, however, are alike. Some novice learners share the metacognitive qualifications of experts, albeit to a lesser extent (Elio and Scharf 1990; Elshout et al. 1993; Ertmer and Newby 1996; Rickey and Stacy 2000). These "expert-novices" rapidly acquire domain knowledge and subsequently apply that knowledge during problem-solving.

The relevance of metacognition in inquiry or discovery learning for science education is substantiated by its omnipresence in the literature for the domains of physics (Anderson and Nashon 2007; De Jong and Van Joolingen (1998), Klein 2004; Koch 2001; Kuhn 1999; Kuhn et al. 1995; Manlove et al. 2007; Schauble et al. 1993; Veenman et al. 1994, 1997, 2002), chemistry (Kipnis and Hofstein 2008; Kozma 2003; Rickey and Stacy 2000; Veenman and Spaans 2005), and biology (Veenman et al. 2004; Zohar and Ben David 2008). An important distinction in inquiry learning is the theorist vs. experimenter position (Klahr and Dunbar 1988), reminiscent of the expert-novice vs. poor novice distinction. Theorists are hypothesis-driven (Shute and Glaser 1990), as they first generate hypotheses and only then test these hypotheses by experimentation. Experimenters, on the other hand, are data-driven (Shute and Glaser 1990). They first generate data and then try to explain their results "bottom-up." Experimenters are less efficient researchers in terms of the number of experiments needed to arrive at a conclusion, relative to theorists. Inquiry learning, either in the real world, in the lab, or in computer-supported environments, presents the novice learner with an open-ended task. Performing such an unstructured task draws heavily on goal orientation and planning (Schauble et al. 1993). Goal orientation and hypothesis generation restrict the universe of alternative actions. An important metacognitive feature of planning in inquiry learning is variable control (Chen and Klahr 1999). Proficient novice learners systematically vary only one variable at the time, whereas poor novices tend to vary two or more variables between experimental trials (Kluwe et al. 1990; Kuhn et al. 1995; Shute and Glaser 1990; Veenman et al. 2004; Zohar and Ben David 2008). The hypothesis-driven and variable-controlled actions of proficient novice learners also allow for more adequate monitoring and evaluation processes (Schauble et al. 1993; Veenman et al. 1997, 2004).

The role of metacognition in writing is rather underexposed in the literature on science education (Armstrong et al. 2008; Connor 2007; Klein 2004; Zohar and Peled 2008). In general, writing is an ill-structured, highly strategic task, drawing on metacognitive skills. Hayes and Flower (1986) distinguish three major processes in writing, that is, planning, translation, and revision. The planning phase includes goal orientation, activating prior knowledge about the theme, and direction of the writing process through a writing plan (e.g., a paragraph structure). In the translation phase, the generation of sentences is regulated by monitoring and local repairs of expressions. Eventually, the written text is evaluated in the revision phase. Such an evaluation should address the initial writing goal and review the text at a global level, rather than at the sentence level. More proficient writers go through all phases recursively, while poor writers tend to start with sentence generation and skip revision. In the same vein, Scardamalia and Bereiter (1991) contrasted the knowledge-telling

strategy of poor writers with the knowledge-transformation strategy of proficient writers. Writing as knowledge telling means that the text is generated from memory contents as loosely connected ideas around a topic. Not much strategic activity there. Conversely, knowledge transformation requires the reorganization of memory contents through goal setting and planning. One can imagine two prototypical students writing their reports about a science experiment. One of them merely lists the events that occurred during the experiment, while the other organizes the report around the research question and comes up with a conclusion in the end.

In the field of science education, activities of reading, problem-solving, inquiry, and writing are not called upon in splendid isolation. Students do read and write as they make notes while studying a textbook. During problem-solving, they have to read the problem statement and write down their solution in an orderly way. Science tasks often draw upon such a combination of different activities. Some chapters in this book, however, focus on more specific subprocesses within an activity such as reading. For instance, the Chap. 8 by Dori and Kaberman addresses the role of self-questioning as a monitoring process in reading. Norris and Phillips (Chap. 3) discuss to what extent students tend to evaluate their prior beliefs against disconfirmatory information in a scientific report.

The chapters of this book, however, explore the role of metacognition in additional areas, such as critical and reflective thinking, the increasing role of computer-based learning in science education (cf. Azevedo 2007), and collaborative learning processes in science education (cf. Kneser and Ploetzner 2001; Van Boxtel et al. 2000). Altogether, the chapters of this book provide a kaleidoscopic view on the role of metacognition in science education.

Concluding Remarks

In this chapter, we have traveled a long way from the early roots of metacognition in Theory of Mind to metamemory and conditional knowledge as part of metacognitive knowledge, to metacognitive strategies and skills, and, finally, to depicting the role of metacognitive skills in science education. It was shown how declarative metacognitive knowledge, in particular conditional knowledge, feeds into the acquisition process of metacognitive skills. Moreover, a comprehensive theory on metacognitive skills as self-instructions was presented, relating Nelson's model to Anderson's ACT theory. The generality of metacognitive skills was illustrated by the converging features of metacognitive skillfulness for reading, problem-solving, inquiry learning, and writing in science education. Orientation, goal setting, planning, monitoring, and evaluation are indispensable for all learning processes in science education. Only reflection is not always mentioned, which is perhaps due to its occurrence after task completion.

The general nature of metacognitive skills has implications for the instruction and training of those skills. Preferably, metacognitive instruction should be given by all science teachers simultaneously in order to achieve transfer across tasks and

sub-domains of science education (Veenman et al. 2004). In an exemplary study by Pressley and Gaskins (2006), students with a very low reading ability were admitted to a special "Benchmark" school, where all teachers of all school disciplines would address the students with metacognitive instructions for reading throughout the day. After four to eight years, these students returned to regular education, while scoring in the upper end of the distribution of reading achievement for same-age students. Certainly, such a synchronized teaching program requires great administration and teaching commitment and coordination, but the long-term results are precious.

There are three fundamental principles for the successful instruction of metacognitive skills (Veenman 2011; Veenman et al. 2006). Firstly, metacognitive instruction should be embedded in the context of the task at hand in order to allow for connecting task-specific condition knowledge (the IF-side) to the procedural knowledge of "How" the skill is applied in the context of the task (the THEN-side of production rules). Secondly, learners should be informed about the benefit of applying metacognitive skills in order to make them exert the initial extra effort. Finally, instruction and training should be stretched over time, thus allowing for the formation of production rules and ensuring the smooth and maintained application of metacognitive skills. Any successful instructional program abides with these three principles.

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Chapter 3
Reading Science: How a Naive View of Reading Hinders So Much Else

Stephen P. Norris and Linda M. Phillips

Focus of This Chapter

Several national bodies have proposed that reading about new scientific findings could serve a useful purpose in citizens' lives. For example, groups in Canada (Council of Ministers of Education Canada 1997), the United States (National Research Council 1996), and the United Kingdom (Millar and Osborne 1998) all have expressed the viewpoint that school science education ought to provide sufficient background for citizens to read reports of new scientific findings appearing in the popular press. By this viewpoint, we assume they mean that citizens should be able to make sense of what they read and be able to make logical inferences about their existing scientific beliefs – whether to maintain or alter them in light of what they have read. However, we know from several decades of research that, even after extended classroom instruction, many scientific concepts defy easy understanding and many erroneous beliefs persist despite disconfirmatory evidence. We know disconfirmatory evidence can be misconstrued, even as confirmatory of existing beliefs. We also know that beyond the difficulty with scientific concepts themselves, readers have difficulty grasping the epistemology inherent in scientific text (such as the degree of certainty being expressed or the relationship between conclusions and reported evidence) and using it to help modulate their scientific beliefs.

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What are readers to do? At a minimum, they need to resist credulity and the tendency to accept misinformation with accurate and honest appraisals of what they understand, of the support that they have for their existing beliefs, and of the evidence in what they read both for the maintenance and the alteration of those beliefs. Such appraisals fall under the category of thought normally labeled "metacognition" (Brown 1985). In metacognition, individuals think about their own thinking, and, in the best of situations, do so critically. Reading metacognition, broadly speaking, is thinking about thinking while reading. Reading metacognition includes the monitoring and control (jointly, the regulation) of thinking while reading: "How well do I understand the last passage? Should I reread it? In what way does it relate to the first two paragraphs? Perhaps I should look up that unusual word in the dictionary. How does this article fit with the one I read last week?" The regulation occurs in the context of beliefs about reading (Baker and Brown 1984; Israel et al. 2005). More specifically, reading metacognition depends upon a normative view of reading, that is, a view of the goals of reading and of what counts as good reading. Metacognition involves making evaluative judgments about, say, the sense one has made of a passage, against a backdrop of the standards and norms provided by one's view of reading. As people's views of reading differ, their metacognitive judgments can differ in response. For example, we know there are those who believe that reading simply is being able to identify all the words. A slightly more sophisticated view of reading, but nevertheless an impoverished one, held by other readers is that reading well is being able to locate information in the text. An even more sophisticated view is that reading is constructing an interpretation that is consistent and takes into account completely the relevant evidence available in the text and the reader's background knowledge. It is easy to see how metacognitive judgments might differ according to the view of reading held. The first reader might ask: "Did I identify all of the words?" If the reader judges the answer to be positive, then the reader has the grounds to think the reading has gone well. The second reader might ask: "Can I locate the important information in the text?" The third reader might ask: "Have I made sense of the text in my interpretation?" In the second and third cases also, a positive answer leads to the judgment that the reading has been successful. Clearly, though, the grounds required for positive assessments differ across the three cases, and the reading that has taken place would also differ from case to case in both depth and breadth – the first and second readings being the most superficial and the third being the deepest.

In this chapter, we focus on two types of metacognitive judgments made by students reading the popular scientific press: Judgments about the difficulty of the texts to read and judgments about the effect of what they have read on prior beliefs. Both of these judgments relate to the monitoring function of metacognition. These judgments can affect how readers subsequently control their reading, a point that will be made clear in several examples that follow. These metacognitive judgments consistently were made poorly by students because, we argue, the students possessed a limited view of the nature and goals of reading. Their view of reading determined the stance they adopted towards the texts. Consequently, the control of their reading also was not effective.

In section "Cognitive Performance: How Well High School and University Students Read Science," we shall describe how well students actually interpreted the popular scientific reports, and where their strengths and weaknesses tended to lie. These strengths and shortcomings fall into the cognitive realm. In section "Metacognitive Performance: What Students Made of Their Reading," we turn to the metacognitive and examine what, upon reflection, the students made of their reading. In section "How to Account for the Results," we offer an interpretation of what was happening for the students to perform as they did and to make the metacognitive judgments they did. Our interpretation is offered in light of a view of reading that we have reasons to believe the students possess. Finally, in section "Educational Policy," we offer several educational policy implications of this work.

Cognitive Performance: How Well High School and University Students Read Science

In our first studies in this area (Norris and Phillips 1994; Phillips and Norris 1999), we selected students in their senior high school year who were enrolled in at least one of senior-year biology, chemistry, or physics. These students were taking or had completed on average about four senior high school science courses. We chose a leading high school in which the student population was relatively homogeneous: Virtually all students were white, middle class, and spoke English as their first language. The students sampled were among the top science students in the school. We next studied undergraduate university students, who on average had taken eight additional single terms of science beyond high school. As such, these university students had an education in science that was far in excess of the average nonscientist, and even the high school students would rank near the top of society in number of science courses completed. We selected our samples in order to get an estimate of the upper bound on nonscientists' ability to read scientific text. We assumed that the average nonscientist could not perform as well as these students.

We devised a set of interpretive tasks that were built around authentic popular reports of science that had appeared in mainstream newspapers and magazines. All of the reports were written for the general, nonscientific public. Five examples follow.

Weather Can Make You Sick

This report (Weinhouse 1992) was on the link between weather and sickness. Statements in the report were offered with varying degrees of qualification, but it was difficult to discern any systematic pattern of qualification that swayed the article either toward or away from the view that weather and sickness are causally related. A critical reader could conclude on the basis of the report that there is some

scientific basis to the claim that weather can make one sick, but would know that further study is required to accept any of the causal connections suggested in the report.

New Animal Species Found in Vietnam

This report (New animal species found in Vietnam 1992) dealt with the possibility of a new species of goat having been discovered in Vietnam. Although the title of the report was quite definitive about the discovery of a new species, it is clear from qualifications throughout the report that the evidence must be examined further before its meaning is known. The critical reader would avoid being misled by the title and adopt a cautionary stance towards the discovery. (Please see the Appendix where this report may be found in its entirety.)

Breakfast of Champions

A further magazine report discussed evidence on breakfast being good for one's health (McDowell 1992). It was made clear by the report that the evidence is suggestive that eating breakfast could lower the risk of early morning heart attacks, the most prevalent kind. The critical reader would note the lack of definitiveness while also seeing the power of the evidence.

Researchers Take Theory on Cow's Milk-Diabetes Link a Step Farther

This report (Taylor 1992) was about the link between drinking cow's milk as an infant and developing juvenile diabetes. The tone of the report was cautionary, maintaining that the new evidence implies, but does not prove, that a link between cow's milk and diabetes exists, and the critical reader would interpret the report this way. Furthermore, the critical reader would note that no clear guidance about feeding cow's milk to infants was given based upon the research.

Mysterious Moon

The mysterious moon is the Jovian moon, Europa (Came 1997). The mystery concerns whether or not there is liquid water and ice on the moon. A feature of the report is that the journalistic style results in statements that clearly assert the presence of water only to be qualified substantially in subsequent parts of the report. A critical

reading of the report would require that the entire document be taken into account before reaching any conclusions about the existence of water or ice on Europa.

We asked students to interpret various aspects of the pragmatic meaning of the reports, by which we refer to meanings that the authors clearly intended but did not state explicitly in the reports. These pragmatic meanings included the expressed degree of certainty with which statements were reported (truth to falsity with gradations in between); the scientific status of statements (e.g., whether the statements were causal generalizations, observations, motivations for doing the research, or descriptions of method); and the role of statements in the scientific reasoning (e.g., whether the statements were justifications for procedures, evidence for conclusions, conclusions, descriptions of phenomena, explanations of phenomena, or predictions). We chose tasks of this nature because they demanded interpretations that went beyond the literal, or surface meanings, of the text to involve discernments of the epistemology underlying what was written. It is such epistemological meanings that show whether readers grasp the connections implied among the statements in the text rather than see merely the individual meanings of statements taken one at a time. At a deep level, it is these epistemological meanings along with the substantive scientific concepts that contain the science.

Based upon our experience with the high school students, we developed an additional information-location task for the university students. For each question that required them to make an interpretation, we asked them to identify where in the reports they found the information they needed to answer it. The students' responses to these questions provided crucial insights into their performance on the interpretive tasks. Our hypothesis was that the students would be much more adept at locating the relevant information in the text than they were at interpreting that information. We knew from previous studies (see Norris and Phillips 2008) that students performed almost identically, answering the sort of multiple-choice questions found in standard tests of reading comprehension, regardless of whether those questions were based upon passages the students reasonably could be expected to understand or upon passages we knew for certain they did not understand. For instance, in one case, we based a set of questions upon a particularly esoteric passage taken from an advanced text in quantum mechanics and witnessed no degradation in their performance. Our explanation is that the types of questions found on standard tests of reading comprehension do not require readers to understand but merely to locate information. Therefore, if the interpretive tasks about pragmatic meaning that we had devised were any better at measuring understanding than standard reading comprehension tests, then the university students should have performed better on the information-location tasks than on the interpretive tasks. (Please see the Appendix, which contains more details on the tasks provided students.)

So, what did we find? There were several salient results from our interpretive tasks. First, the high school students demonstrated a certainty bias that skewed their interpretations of the expressed degree of certainty of statements towards being more certain than their authors had written them. That is, if a statement was expressed as likely being true, students would tend to interpret it as true; if it was expressed as

uncertain, students would tend to interpret it as likely to be true or even true; if the statement was expressed as false or likely to be false, students would miss this meaning altogether and interpret the statement as having some degree of truth. Second, students were less able to interpret the role of statements in the scientific reasoning of the reports than they were able to interpret the scientific status of statements taken one at a time. The difference was quite large, with less than one half able to interpret the role of statements and about 90% able to identify the nature of statements that could be assessed independently of others. The difference seemed to be due to a weaker ability to interpret statements whose role could be inferred only by recognizing the implied connections to other statements. For example, when literal interpretation alone provided significant cues, such as frequently is the case with observation statements ("We observed that…"; "We saw that…"; "We noticed that…") and reports of method ("We measured the…"; "We attached the probe to…"), their performance was good. However, when faced with such questions as whether a statement was evidence for a conclusion in the report or a conclusion based on evidence, an explanation of a phenomenon described in the report, a prediction from an idea being tested, or a motivation for doing the research, their performance deteriorated substantially. This result suggested to us that students read for meaning only at a superficial and local level, rather than at a deeper level that examined for connections across the text.

We found that the university students performed almost identically to the high school students. They showed the same certainty bias, systematically overestimating the degree of expressed certainty in the reports; the same strength in identifying observation and method statements; and the same weakness interpreting the role of statements in the reports' reasoning, confusing statements providing evidence for conclusions with the conclusions themselves, and misinterpreting descriptions of phenomena with explanations of those phenomena. The key for us was the fact that their substantially increased science education did not help them on any of these tasks. However, whereas the university students answered only about one-half of the interpretive questions correctly, they correctly identified the place in the report with the needed information (the information-location tasks) about three-quarters of the time. This finding confirmed our suspicion that the students would perform better on the information-location tasks than on the interpretive tasks, and provided evidence that our interpretive questions were tapping an aspect of reading performance normally not measured by standard reading tests. In the following section, we begin to forge links between these cognitive aspects of students' performance and their metacognition.

Metacognitive Performance: What Students Made of Their Reading

We first turn to the metacognitive tasks that were presented to the university students (Metacognitive tasks for both university and high school students may be found in the Appendix). They were asked for each report how difficult they found it to read

(very difficult, difficult, about right, easy, and very easy). This is a metacognitive task that requests students to think about their thinking while they were reading and to report the extent to which they faced interpretive difficulties. Although the task was retrospective, it was presented right after reading the reports and thus can be taken as a good approximation of their perceived reading difficulty while reading (Norris 1990). At most, only 5% judged that any report was very difficult to read, more than one half claimed finding the reports easy or very easy, and more than 90% found the reading difficulty to be at least about right. That is, their metacognitive self-assessments of the reading difficulty of the reports underestimated dramatically the demands of the report and the cognitive difficulty they experienced with the interpretive tasks. Moreover, there was only the weakest of relationships ($R^2 = 0.06$) between the students' perceived difficulty in reading the reports and their performance on the interpretive tasks, that is, between their metacognitive judgments and their cognitive performance. For instance, although about 40% of the students found the axis of the universe report (one given only to the university students) very difficult or difficult to read (all the other reports were below 8% on these categories), the students performed hardly any differently on the interpretive tasks between the axis of the universe report and the other reports. We believe that these results are key to understanding the difficulty that students experience reading scientific text. If students make inaccurate judgments when monitoring their reading, for example, about the difficulty they are experiencing, then they are unlikely to take effective control of their reading, for example, to adopt strategies that might ease or compensate for their difficulty.

Another metacognitive task addressed the interest in how students' beliefs can be altered by scientific views of the world represented in text (McCloskey 1983; Park and Pak 1997). We asked the high school students questions that probed the relationship between the content of the reports and their beliefs. Before reading each report, they were asked a question about their background beliefs on the topic. For instance, before reading the weather and sickness report, students were asked the following: "Do you believe that the weather can make you sick? Why do you say that?" Before the report on breakfast and heart attacks, they were asked whether breakfast is good for one's health and why they believed what they did. Before the report on the possible discovery of a new animal species, they were asked whether they believed new animal species were still being discovered and why they believed what they did. Before the report on cow's milk and diabetes, they were asked: "Do you believe that women should breast feed their babies? Why do you say that?" Having answered the questions, they were instructed to turn the page and read the reports. After reading each report, they were asked the metacognitive question whether they were now more certain, less certain, or equally certain of their previous view, and to say why.

It is instructive to analyze students' responses in light of the nature of the reports. Consider first the breakfast report. That report supported a "yes" response to the question of whether breakfast is good for one's health, and 95% of students gave a "yes" response before reading the report. After reading the report, slightly more than one half of the students were more certain that breakfast is good for one's health, about one third were equally certain, and fewer than 10% were less certain.

We interpret this response pattern as follows. Almost all the students thought before reading the report that breakfast is important. After reading a report that confirms this point of view, slightly more than half of the students were more certain of their opinion. This is a reasonable metacognitive judgment, because they have found confirmation for their view and have thus become more confident in it. About one third of the students were equally certain in their view after reading the report. This is also a reasonable position. The report confirmed their original view, but confirmation does not lead necessarily to greater certainty. Sometimes, for example, confirmation is redundant, which could have been the case for these students. A small minority of students was less certain in their view, and the vast majority of these had also responded originally that they thought breakfast was good for one's health. These students thought before reading that breakfast is important, read a report that confirmed this view, and then claimed to be less certain afterwards. This clearly is not a logical position to take. Perhaps, given the small proportion of students involved, the result could be attributed to a misinterpretation of the report or to some other source of response error. Although these possibilities are interesting, we are more interested in other conflicts that appeared in students' responses. To such matters, we now turn.

Focus now on the new animal species and cow's milk reports. The response patterns for these two reports were almost identical to the breakfast report, that is, roughly the same proportions of students replied affirmatively to the questions asked prior to reading, and roughly the same proportions were more, less, and equally certain of their original positions after reading. However, and here is the rub, neither the new animal species nor the cow's milk report supports a "yes" or a "no" response to the questions asked prior to reading. That is, the reports are neutral on whether new animal species are being found and on whether mothers should breast feed their babies. Yet, nearly all of the students responded "yes" to the original questions, and more than one half of them claimed to be more certain of their views after reading the reports, even though the reports did not support any increased certainty. These results for the new animal species and cow's milk reports call into question the reasonableness of the response pattern to the breakfast report, making us wonder whether the reasonableness of that pattern is more a matter of coincidence than some underlying level of reading competence.

Finally, consider the weather and sickness report to see how the students' responses can be even more puzzling, even perverse! This report also supports a "yes" answer to the initial question of whether weather can make one sick, but this was the report for which the smallest proportion of students responded "yes" and for which the highest proportion of students expressed qualifications. We also see a different pattern of expressed certainty after reading the report, with the largest proportion of less certain students for any of the reports, nearly one third compared to less than one tenth in all other cases. We examined students' responses to this report more closely. Of the students who responded "no" originally (about 14% of the total number of students), three fourths were less certain of their original response after reading the report. This is a logically sound position given the report's support of a "yes" response. However, of the students who responded "yes" originally

(about 80% of the total number of students) nearly one fourth were less certain after reading the report. We examined their reasons, and nearly all of these students gave the same type of response. The students' reasons tended to derive from local lore about weather and health, such as that damp weather aggravates arthritis. In no case, however, were the reasons offered by the report contradictory to the reasons offered by the students – they merely were different. Thus, even though the students gave "yes" responses to the original question, and even though the report supported those responses, they were less certain in their responses after reading the report because the report had offered different reasons than they had offered.

At this point, we struggle to discern any understandable connection between students' prior beliefs, their cognitive interpretations of what they read, and their metacognitive judgments of how what they read bears upon their prior beliefs. In no way can we understand the connection as reasonable. If such connections are not reasonable, effective metacognitive control of reading appears to us impossible. If sensible connections are not made between prior beliefs, the information in the text, and beliefs after reading, then sensible judgments cannot be made about whether one's reading is adequate or requires some corrective action.

In the following section, we attempt to pick up the pieces – to explain the unreasonableness of the connection between the high school students' prior beliefs and their judgments of how their reading bears upon those beliefs, and to explain the mismatch between university students' expressed ease in reading the reports and the actual standing of their interpretive performance. Both phenomena, we will argue, are traceable to the same underlying cause – students' metacognitive views of the nature of reading.

How to Account for the Results

Two features of students' views of reading are revealed in our results. These features work together to create what we have called "a simple view of reading". First, we will examine how the high school students in general demonstrated a marked deference to the reports when we asked them to relate what was in the reports to their prior knowledge. We categorized their stances toward the reports either as *text-based* (maintaining certainty in a belief solely on the basis that the report says it or that the report agrees with their preexisting beliefs), *background-belief-based* (forcing interpretations on the reports in order to bring them in line with their preexisting beliefs), or *critical-based* (adjudicating their background beliefs and the reports in light of one another and on the basis of reasons in order to construct new or revised beliefs).

The pattern of student responses described in section "Metacognitive Performance: What Students Made of Their Reading" can be understood partly by examining students' adopted position with respect to the reports. In adjudicating their prior beliefs against what they read, more than two thirds of students adopted text-based positions. They either deferred absolutely to the reports, simply paraphrased the

reports to support their position, or agreed with the reports on the grounds that their own beliefs and the text coincided. Slightly fewer than 20% adopted a background-belief-based position by imposing interpretations on the text to accord with their own background beliefs. In the text-based responses, what Olson (1994) called "the world on paper" overrode the readers' worlds; in the background-belief-based responses, the readers' worlds overrode the world on paper (Phillips and Norris 1999). Both of these response types are uncritical. Only a minority of students adopted critical positions, either by giving good reasons why the reports should be believed (at most 17% for any report), or by taking issue with the text on the basis of good reasons (at most 10% for any report).

As mentioned in section "Metacognitive Performance: What Students Made of Their Reading," there was no systematic relationship between students' degrees of certainty in their beliefs and the support that the reports offer for them. In examining their reasoning, we saw that the lack of connection was due to students' failure to integrate well their background beliefs and the text information. This result is consistent with other research that has illustrated the tendency for ideas, once formulated or adopted, to persist despite disconfirmatory evidence (Beal 1990; Holland et al. 1986). The majority of students deferred to the reports by readily accepting the statements in them and by implicitly trusting the authors. Only on rare occasions did readers challenge the authority of the reports or the authors. Few students appraised the reports against their background beliefs. Thus, the agreement or disagreement between the scientific beliefs students held before reading the reports and what the reports said had extremely little to do with the scientific beliefs they held after reading the reports. If students were less certain about their initial beliefs after reading a report, then their diminished level of certainty presumably would be on the grounds that the report was sufficiently persuasive and credible to alter their initial position. For those students who expressed more certainty about their initial beliefs, the same response would be expected. However, those students who expressed either less or more certainty about their background beliefs tended to do so, not on the basis of a critical evaluation of the text, but on the basis of mere deference, echoing, or affirmation of the text. Only for the weather and sickness report did a sizable number of students who expressed either less or more certainty critically evaluate the report. The most influential factor in students' judgments seemed to be what the reports said and not whether and why the reports should be believed. Hence, for most of these students, rather than integrating the two worlds, the world on paper weighed supremely over their own cognitive worlds. Thus, the goal of students' approaching "[science] reading as an interactive-constructive process and science learning as something more than conditioned responses and rote memorization" (Holliday et al. 1994, p. 879) seems not to have been reached by these students.

We can now circle back to the university students who reported finding the media reports easy to read but performed poorly on the interpretive tasks we set for them. Why did they interpret poorly? From our experience with the ability of individuals to perform very well on standard reading assessment tasks in spite of the fact that the passages are beyond even their modest understanding, our conjecture is that the

interpretive tasks we designed required these students to go beyond decoding words and locating information in the text, which is a sufficient basis for most standard reading assessment tasks (Collins Block and Pressley 2002; Pressley and Wharton-McDonald 1997), although insufficient for authentic reading. We had asked them to infer connections between statements that often were widely separated in the text; they were asked to infer pragmatic meanings that often were not literal; in short, they were unable to make interpretations that went beyond the literal. However, why did they report finding the passages of suitable reading difficulty? Our hypothesis is that their view of reading led them to this conclusion. They knew they could identify the words, and they knew they could locate information (a confidence justified by our direct assessment of their information-location ability). Therefore, all of their school and university experience told them that they had read successfully, even though they had not.

According to the simple view, reading means word recognition and information location, and it is a view that has been documented and regretted widely (e.g., Baker and Brown 1984; Collins Block and Pressley 2002). Sadly, although according to their simple view of reading they had read, they did not understand. More sadly, their view of reading was not up to the task of helping them to see that they had not understood. The simple view aims to reduce reading to word recognition and location of information, but fails because it is easy to demonstrate how the satisfaction of these criteria can be achieved without understanding in any deeper sense than grasping surface meanings.

Why did the university students perform on the cognitive tasks no better than high school students who had much weaker science backgrounds? That is, why did their science background appear not to help? It is widely believed that more background knowledge is associated with improved reading comprehension. Phillips (1988) supplies a possible explanation of the lack of relationship between students' science backgrounds and their performance on the tasks we set for them. She found that sixth grade readers' background knowledge mattered only in the context of reading proficiency defined by the use of what she called "productive reading strategies," which include questioning your interpretations and considering alternative ones. Students in her study who used such productive reading strategies were able to compensate somewhat for their lack of background knowledge, although the best reading was found in the context of both productive strategies and background knowledge. The productive reading strategies used by the children corresponded in a large measure to those identified by Collins et al. (1980) in their study of skilled adult readers, and strongly overlap with strategies often associated with the monitoring function of metacognition, because they point to ways to think about thinking while reading: Have I considered alternative interpretations? Does my interpretation take into account all of the textual information? Am I able to confirm my interpretation? Am I empathizing with the experiences of the characters? (Norris and Phillips 1987). Therefore, it is reasonable to surmise that many of the university students in our study lacked metacognitive strategies for reading the type of text found in the media reports of science. Else, they would have been able to capitalize upon their superior scientific knowledge and outperform the high school students. Needless to say, such

strategies as questioning one's interpretations and seeking alternative ones are not the type employed by those readers concerned primarily with identifying words and locating information.

Consider an example. It is one thing to read in a media report of science these very words about the Jovian moon, Europa: "beneath the moon's frozen crust an ocean surges" (Came 1997, p. 42). It is quite another matter to read these words in the context of the whole report about new pictures showing jumbled icebergs and cracked ice fields, and to recognize that the statement being put forward is not a factual assertion. Rather, the statement is a tentative interpretation of evidence. The entire context must be examined and taken into account in order to come to this recognition. To proceed without taking into account the entire context is to act as if words and strings of words can be taken in isolation and their meaning known. Reading the entire text, we find not far removed from the previous words these additional words: "Last week, those suspicions [that there is an ocean below Europa's frozen surface] received a powerful boost…" and "It [pictures of jumbled icebergs and cracked ice fields] is the clearest evidence to date of liquid water and melting close to the surface…". Further removed from the original words, we find ones such as: "The size and geometry of these features lead us to believe there was a thin icy layer covering water or slushy ice…" and "Not even NASA's scientists have a precise idea of what may have prompted Europa's ice to move" and "… it all suggests movement of some sort, like polar ice during spring thaw." What starts as an apparent assertion of an ocean below Europa's surface transforms upon further reading into a hypothesis. It is a very tentative hypothesis, because the very phenomenon the hypothesis is designed to explain – fractured, shifting, and rafting ice – is called into question. The movement of ice is itself a hypothesis from the photographic data.

Now, let us examine some additional data from the university students' responses. First, let us look at their judgment of the expressed degree of certainty in the statement, "There is liquid water and melting on Europa." We interpreted the statement as having *uncertain truth status* – it represents a hypothesis that is still under early stages of testing. Only 19% of students judged it as such, while 25% judged it to be *true,* and 52% judged it as *likely to be true*. At the same time, about 95% of these students judged the report to be *very easy*, *easy*, or *about right* to read. Our interpretation of these findings is that the students judged the reading difficulty of the report to be manageable because they knew the words and were able to locate information: they had the naive, simple view of reading. They did not realize that they were not making interconnections among noncontiguous pieces of information in the same text. They were unable to interpret what Glynn and Muth (1994, p. 1060) referred to as the conceptual relations "woven into well-written scientific text." Whereas in the data from the high school students we see a marked deference to text, in the data from the university students we see accomplished attention to detail without a comparable attention to the message as a whole. These two features of students' reading actually go together. Attention to word recognition and isolated pieces of information leads to an overinflated view of ability to read for those who do recognize the words and can locate the information. Also, attention to the words, without atten-

tion to what the author is trying to convey with those words (the distinction between what the words say and what the words mean), leads to an unanalytical and uncritical approach to reading. Barring analysis and criticism, all that remains is deference and acceptance.

Clearly, then, the simple view of reading does not address what we wish to achieve in science education. Sophisticated reading, in contrast to what the high school and university students tended to exhibit, requires a level of cognitive and metacognitive expertise that enables sound interpretations at a variety of levels. We like Olson's concept of literate thought as a means of capturing very significant aspects of metacognition. The key to reading on his view is the mastery of literate thought, which brings the thinking involved in reading to a conscious level. "Literate thought is the conscious representation and deliberate manipulation of [the thinking involved in reading]. Assumptions are universally made; literate thought is the recognition of an assumption *as an assumption*. Inferences are universally made; literate thought is the recognition of an inference *as an inference*, of a conclusion *as a conclusion*" (Olson 1994, p. 280). It is literate thought conceived in this way that governs performance on the sorts of interpretive tasks that we have described, because it addresses several key aspects of the monitoring function of metacognition. If readers do not recognize when they are making assumptions and inferences and drawing conclusions, they can hardly effectively monitor the quality of their reading and are missing the input needed effectively to control its direction. In addition, sophisticated reading requires metacognitive appraisal that provides an accurate gauge of the quality of one's interpretations, of how what one is reading ought to interact with what one already believes, and, more generally, of the stance that one ought to adopt with respect to a text.

In contrast to the naive, simple view of reading as decoding words and locating information, we offer a view of reading as inferring meaning from text through the integration of text information and the reader's knowledge. This integration creates something new, over and above the text and the reader's knowledge – an interpretation of the text (Phillips 2002). It is crucial to understanding this view to recognize that interpretations go beyond what is in the text, what was the author's intent, and what was in the reader's mind before reading it. Also crucial is the position that not all interpretations of a text are equally good, but usually there can be more than one good interpretation. The possibility of more than one good interpretation exists for all text types, notwithstanding the fact that the leeway for proposing multiple interpretations varies from type to type (Norris and Phillips 2003).

The above conception of reading implies a relationship between authors, their texts, and the readers of those texts. Readers are pictured making an array of judgments about text that go beyond surface meaning: Including judgments about what is meant or intended in contrast to what is said, what is presupposed in what is said and meant, what is implied by what is said and meant, and what is the value of what is said and meant (Applebee et al. 1987; Bereiter and Scardamalia 1987; de Castell et al. 1986; Torrance and Olson 1987).

From our perspective, reading has a number of features (Norris and Phillips 1987). First, reading is *iterative*. By this we mean that reading proceeds through a number

of stages that move between the cognitive and metacognitive, each aimed at providing a more refined interpretation: Lack of understanding is recognized; alternative interpretations are created; judgment is suspended until sufficient evidence is available for choosing among the alternatives; available information is used as evidence; new information is sought as further evidence; judgments are made of the quality of interpretations, given the evidence; and interpretations are modified and discarded based upon these judgments and, possibly, alternative interpretations are proposed, sending the process back to an earlier step. Second, reading is *interactive*. Interaction takes place between information in and about the text, the reader's background knowledge, and interpretations of the text that the reader has created, again moving between the cognitive and the metacognitive: Judging whether what they know fits the current situation; conjecturing what interpretation would or might fit the situation; and suspending judgment on the conjectured interpretation until sufficient evidence is available for refuting or accepting it. The reader actively imagines, and negotiates between what is imagined and available textual information and background knowledge. Finally, in order to carry out such negotiation, reading is *principled*. The principles guide both cognitive interpretations and metacognitive judgments. Completeness and consistency are the two main criteria in both cases. Neither criterion by itself is sufficient; they must be used in tandem. Readers must ask which interpretation is more complete, and more consistent, because often neither interpretation will be fully complete and fully consistent.

Reading, then, means analyzing, interpreting, and critiquing texts. In order to engage in the metacognition needed to monitor and control such processes, readers require an elaborate repertoire of basic understandings of texts. On our view of reading, reading resembles science, in that it involves many of the same mental activities that are central to science (Gaskins et al. 1994; Norris and Phillips 2008). Moreover, when the reading is of science text, it encompasses a very large part of what is considered doing science. It is not all of science because it does not include manipulative activities and working with the natural world. However, the relationship between reading and science is intimate. Science educators need to be concerned, therefore, by the possibility that many students will bring to their science learning the simple view of reading. If science teachers do not emphasize the expansive nature of reading, then they are likely to reinforce the attraction that this simple view has.

Educational Policy

If citizens are unable accurately to interpret popular reports of science and, furthermore, are disposed to defer to them, then teaching them more of the substantive content of science will not help. How readers appropriate the relationships within texts depends upon the cognitive and metacognitive strategies and the repertoire of knowledge they bring from their worlds, and what happens when their worlds and the world on paper meet. Students must learn to take a critical stance toward

texts, or we can do no more than teach them to remember what reports of science say. Such superficial memorization is not likely to achieve the good for citizens and society that we all desire. Rather, more concerted attention to generalizable literacy skills and attitudes is a better bet.

A view that underlies this chapter is that science teaching is in part a literacy project. For many science teachers, seeing themselves as literacy teachers would require a radical shift in their self-conception. However, in adopting the role of literacy teacher, science teachers would play a role more central to education than the teaching of science. Science teachers would teach the concepts, skills, understandings, and values that are generalizable to all reading and that find application within science. In order to achieve this transformation in teacher outlook, much curriculum work and teacher education needs to take place.

First, much more emphasis is needed on teaching and learning how to read argumentative text, that is, text in which reasons and evidence are offered for conclusions. Beginning reading programs once contained almost only narrative selections for students to read. This domination by narrative is slowly coming to an end, but its replacement hardly ever includes argumentative text (Phillips et al. 2005). Rather, what is found is more informational and expository text that, like current science textbooks (Penney et al. 2003), tends to emphasize word recognition and information location – just the focus that needs to be downplayed. There is a need for more emphasis on teachable cognitive and metacognitive reading strategies for dealing with argumentative text, and for persistent pressure on the educational system to take seriously explicit instruction in the early school years on reading and writing argumentative text. Unless students recognize the need for, and know how to make, the sorts of pragmatic meaning interpretations of scientific texts that we have discussed (those concerning expressed certainty, scientific status of statements, and the role of statements in scientific reasoning), they are not likely to be able to make accurate assessments of the difficulty of texts. Likewise, they are not likely to make sound judgments about the effects of what they have read on their existing beliefs. Thus, the cognitive and metacognitive come together, with the performances of the former providing the focus for the judgments of the latter.

Second, it would be helpful to articulate for science educators a clear rationale for the scientific practices with text that ought to be brought into the science classroom. The rationale would be partly value driven by referring to and justifying the goals that would be achieved, but also empirically driven by drawing on available research on which practices work and which do not. There are many questions that need to be explored, including ones about the type of texts that might achieve the most desirable ends – genuine scientific research reports, genuine reports suitably translated for particular levels of schooling (Baram-Tsabari and Yarden 2005; Phillips and Norris 2009; Schwab 1962), or fictional texts purposely designed and created for the situation.

Third, and related to the second point, on the assumption that textbooks will be around for a long time, we need redesigned textbooks that incorporate more argumentative text and focus on the reading strategies useful for interpreting them. For this to happen, the texts themselves have to be worthy of interpretive attention

and effort, so that students can move away from recall, recognition, and information location. Metacognition is hardly required unless, first, cognition is! Textbooks could start to include more explicit and frequent treatment of reasons for conclusions, examples from frontier science where the scientific community has not reached consensus on an issue, and the use of media reports of science as texts to be interpreted and critically appraised.

Finally, science education needs to pay greater attention to reading science. Reading science is not about simply recognizing words and locating information, as important as these skills are at a basic level. It is mainly about seeing the structure of science in the text. However, in order to see this structure, students require a more sophisticated view of reading. The naive view of reading as word recognition and information location hinders their ability to relate what they read to what they already believe and even to grasp when they have not understood what they have read. A naive view of reading indeed hinders so much else, and the fix is too straightforward to be ignored.

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Appendix: New Animal Species Found in Vietnam

1. WASHINGTON (AP) – A "lost world" teeming with possible new species of birds, fish and an unknown dagger-horned mammal has survived a half-century of war and expanding civilization in remote Vietnam, wildlife experts say.
2. If it proves to be a new species, the U.S. and British scientists said the creature locally referred to as a "forest goat" would be one of only a handful of large mammals newly recorded in the last 100 years.
3. A recent survey of the relatively untouched Vu Quang Nature Reserve by a team from the Vietnam government and the World Wildlife Fund documented preliminary evidence of two previously unknown bird species, at least one new fish, an unknown tortoise with a striking yellow shell and the goat-like mammal. "The horns are quite unlike those of other goats previously recorded," said British scientist John MacKinnon, who led the World Wildlife Fund expedition in May. He said it could be another kind of bovid, or hooved animal.

4. "It's a lost world that modern science had never before looked at," he said in a telephone interview late last week from London.
5. With most of Indochina heavily populated and so ravaged by wartime herbicides and bombing, stepping into Vu Quang is "like opening a door into a lost and neglected place," MacKinnon said. "Biologically, it's not like the rest of Indochina." Officials of the Washington-based World Wildlife Fund said the relatively untouched Vu Quang area spreads over 168 km^2 along a steep stretch of land near the Laotian border, a 10-h overland trip from Hanoi.
6. The team found three sets of upper skulls and horns of the previously unknown mammal, MacKinnon said. While none was spotted alive, one of the skulls still had maggots crawling in it, indicating it had died recently.
7. Skin samples from the hooved beast, which is a target of hunters in the area, will be compared with those from cows, buffaloes, antelopes and goats to see where it falls scientifically, MacKinnon said. Skulls are also being examined by scientists in Vietnam, he said.
8. The Vietnamese are trying to find a better specimen, he said, "but we don't want to encourage actively shooting one because it might be a very rare animal."
9. MacKinnon said he plans to return to the area soon and will set up cameras in the forest. Elephants, tigers and leopards are among animals known to be in the area, he said.
10. In addition to the evidence of a new mammal, MacKinnon said the scientists spotted a small parrot-billed bird that they believe may not be documented, as well as a sunbird that could be a new species and at least one new fish.

Belief Questions

Do you believe that new animal species are still being found around the world? Why do you say that?

How much knowledge of the general topic of the article do you have? Please respond by checking the alternative which best applies to you: No knowledge; Very little knowledge; Some knowledge; Much knowledge. Please explain your choice.

Cognitive Questions

Set 1

Students provided with five statements from the report and instructed: "For each of the statements, decide whether according to the report the statement is, True, Likely to be true, Uncertain of truth status, Likely to be false, False."

"After each statement indicate where in the report you found information to help you decide by writing the paragraph number(s)."

Set 2

Students provided with five statements from the report and instructed: "For each of the statements, decide whether the statement reports: That one thing causes or influences another; That one thing is generally related to another; What was observed; What prompted the scientists to do the research; How the research was done. For each statement, choose only one answer. You may choose the same answer for different statements."

"After each statement indicate where in the report you found information to help you decide by writing the paragraph number(s)."

Set 3

Students provided with five statements from the report and instructed: "For each of the statements, decide whether the statement reports: A justification for what ought to be done; A phenomenon identified and explained in the report; An explanation of a phenomenon; Evidence for or against a hypothesis that has been made; A conclusion drawn on the basis of reasons; A prediction from an idea being tested. For each statement, choose only one answer. You may choose the same answer for different statements."

"After each statement indicate where in the report you found information to help you decide by writing the paragraph number(s)."

Metacognitive Questions

Now that you have read the report, are you more certain, less certain, or equally certain about your answer to [the question of whether you believe that new animal species are still being found around the world]? What made up your mind?

How easy or difficult did you find the article to read?
Very easy; Easy; About right; Difficult; Very difficult
If you chose *Difficult* or *Very Difficult*, please check all that applied to you while reading the article:

You are not familiar with the general topic of the article;
The scientific explanations were complicated;
You have little or no experience reading newspaper reports of scientific research;
The report was not clearly written;
Other (Please explain).

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Chapter 4
Metacognitive Knowledge and Field-based Science Learning in an Outdoor Environmental Education Program

Gregory Schraw, Lori Olafson, Michelle Weibel, and Daphne Sewing

Introduction

Metacognition is an important component of learning and self-regulation at all ages (Efklides 2008; McCormick 2003). Previous research indicates that older students are more metacognitively aware than younger students, but that even students in the lower elementary grades demonstrate metacognitive awareness that is related positively to learning (Presley and Harris 2006). The goal of this chapter is to examine the relationship between different types of metacognitive knowledge, attitudes about environmental education, and learning during a half-day science intervention on a floating laboratory at Lake Mead National Recreation Area. Our chapter is arranged into seven sections. The first section presents a multi-component taxonomy of metacognition and related terms. The second section describes the development of two self-report instruments intended to measure metacognitive knowledge and regulation. Section three states five predictions of the present research. Section four describes the participants, materials, and research procedures used in our research. Section five presents results, while section six discusses these results and links them to previous research. Section seven explores several ways to improve metacognition.

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Taxonomy of Metacognition

Metacognition is a broad term that is usually interpreted as *thinking about thinking* or *demonstrating awareness and understanding of one's cognition* (McCormick 2003). The term metacognition is related to several other terms in the literature usually referred to as metamemory and metacomprehension which distinguish between knowledge about the contents of memory versus processes used to regulate and monitor memory and cognition. The term *metacomprehension* appeared later and refers to understanding at the broadest level of comprehension that is necessary for an individual to be fully self-regulated (Efklides 2008). At least two components of metacomprehension are necessary for comprehensive understanding, including metamemory and metacognition. Given current definitions, metamemory refers to knowledge and understanding of memory in general, as well as one's own memory in particular. This knowledge enables individuals to appraise memory demands and to assess available knowledge and strategies in memory. Metacognition refers to knowledge about cognition and cognitive processes (Schraw 2006). Metacognition usually is subdivided into two distinct components, including knowledge of cognition and regulation of cognition. Some researchers also refer to these two components as metacognitive knowledge and metacognitive skills.

The framework used in the present study for conceptualizing metacognition is based on the distinction between knowledge and regulation of cognition (Sperling et al. 2002). Figure 4.1 shows components of metacognition and their relationship to metacomprehension and metamemory. Knowledge of cognition refers to what we know about our cognition and usually includes three subcomponents. The first, declarative knowledge, includes knowledge about oneself as a learner and what factors influence one's performance. For example, most adult learners know the limitations of their memory system and can plan accordingly. Procedural knowledge, in contrast, refers to knowledge about strategies and other procedures. For instance, most adults possess a basic repertoire of useful strategies such as note-taking, slowing down for important information, skimming unimportant information, using mnemonics, summarizing main ideas, and periodic self-testing. Finally, conditional knowledge, includes knowledge of why and when to use a particular strategy. Individuals with a high degree of conditional knowledge are better able to assess the demands of a specific learning situation and, in turn, select strategies that are most appropriate for that situation.

Research suggests that knowledge of cognition is late developing and explicit (Efklides 2008; Kuhn 2000). Adults tend to have more knowledge about their own cognition and are better able to describe that knowledge than children and adolescents. However, many adults cannot explain their expert knowledge and performance and often fail to spontaneously transfer domain-specific knowledge to a new setting. This suggests that metacognitive knowledge need not be explicit to be useful and, in fact, may be implicit in some situations (McCormick 2003).

Regulation of cognition typically includes at least three components, planning, monitoring, and evaluation (Schraw 2006). Planning involves the selection of appropriate strategies and the allocation of resources. Planning includes goal setting,

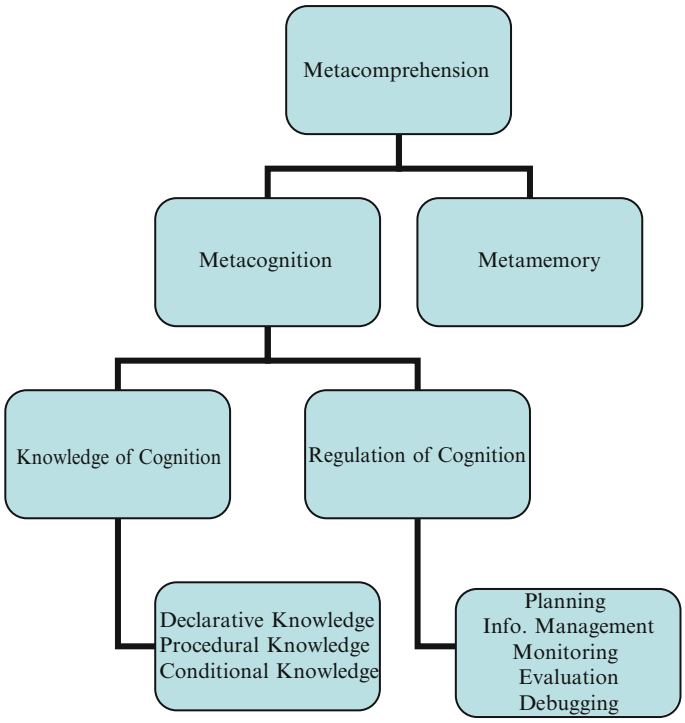


Fig. 4.1 The relationship of metacomprehension, metacognition, and metamemory

activating relevant background knowledge, and budgeting time. Previous research suggests that experts are more self-regulated compared to novices largely due to effective planning, particularly global planning that occurs prior to beginning a task. Monitoring includes the self-testing skills necessary to control learning. Research indicates that adults monitor at both the local (i.e., an individual test item) and global levels (i.e., all items on a test). Research also suggests that even skilled adult learners may be poor monitors under certain conditions (Pressley and Harris 2006). Evaluation refers to appraising the learning and self-regulation of one's learning. Typical examples include re-evaluating one's goals, revising predictions, and consolidating intellectual gains.

Some researchers and theorists believe that self-regulatory processes, including planning, monitoring, and evaluation, may not be conscious or explicit in many learning situations. One reason is that many of these processes are highly automated, at least among adults. A second reason is that some of these processes may develop without any conscious reflection and therefore are difficult to report to others. Some science educators believe that science education should reduce the amount of instructional time devoted to conceptual understanding and increase the amount of time devoted to procedural understanding. The rationale for this claim is that procedural competence in the form of expert problem-solving and critical thinking becomes increasingly more important at higher levels of science education.

Development of the Metacognitive Awareness Inventory

Schraw and Dennison (1994) created an instrument designed to assess metacognitive awareness. The metacognitive awareness inventory (MAI) included 52 statements that measured awareness about knowledge and regulation of cognition (see Table 4.1). Schraw and Dennison (1994) conducted two experiments as part of an initial validation study. Experiment 1 piloted the instrument on 179 college undergraduates and reported a two-factor structure based on exploratory factor analyses. Results supported a reliable two-factor solution. Experiment 2 replicated the exploratory factor analysis reported in Experiment 1 using 100 college undergraduates and added several additional variables, including reading comprehension scores on a 16-item test and calibration judgments for each test item. The knowledge of cognition variable was significantly correlated with test performance and ratings of confidence for test items, but was not related to calibration accuracy. A number of subsequent studies replicated the two-factor structure of the MAI and extended the findings reported above (Mevarech and Amrany 2008).

More recently, Sperling et al. (2002) created a parallel 12-item version of the MAI called the Jr. MAI that was intended for students in 3rd through 8th grade that could be used to assess incoming metacognitive knowledge or changes in knowledge after an intervention to improve metacognitive skills. Sperling et al. (2002) conducted two experiments. Both experiments replicated the knowledge and regulation of cognition factors reported in the MAI. In addition, scores on the Jr. MAI were correlated significantly with scores on the metacomprehension ($r = .30$) and strategic problem-solving ($r = .72$) inventories, as well as teacher ratings ($r = .21$).

Table 4.1 Types of metacognition described by Schraw and Dennison (1994)

Type of metacognition	Skills within each domain of metacognition	Definition
Knowledge of cognition		
	Declarative knowledge (8 items)	Knowledge about one's skills, intellectual resources, and abilities as a learner
	Procedural knowledge (4 items)	Knowledge about *how* to implement learning procedures (e.g., strategies)
	Conditional knowledge (5 items)	Knowledge about *when* and *why* to use learning procedures
Regulation of cognition		
	Planning (7 items)	Planning, goal setting, and allocating resources prior to learning
	Information management (10 items)	Skills and strategy sequences used on-line to process information more efficiently
	Monitoring (7 items)	Ongoing appraisal of one's learning or strategy use
	Debugging (5 items)	Strategies used during learning to correct comprehension and performance errors
	Evaluation (6 items)	Analysis of performance and strategy effectiveness after a learning episode

Metacognition and Science Education

The present study examined the relationship between metacognitive knowledge, attitudes about a field-based science program, and student learning in an environmental education program among 4th and 5th grade students. One important question was the extent to which metacognitive knowledge facilitates science learning. Previous research suggests that metacognition is an extremely important component of science learning for students of all ages (Linn and Bat-Sheva 2006). This literature identified six general instructional strategies that improved learning, including inquiry, student collaboration, use of regulatory learning strategies such as planning and organization, constructing conceptual mental models, use of technology to search and represent information, and incorporating positive personal beliefs such as mastery goal orientations and self-efficacy. Each of these had a positive effect on learning and contributed uniquely to student learning and achievement. In addition, Zohar (2006) found that teachers' metacognitive knowledge and instruction of metacognitive skills increased learning among high school students. Blank (2000) also reported that infusing metacognitive skills into a science learning program improved self-regulation and learning among middle school students. However, the vast majority of these studies were conducted on high school or middle school students; whereas few studies examined the metacognitive knowledge or self-regulation skills of younger students. Similarly, Annevirta and Vaurus (2006) reported that metacognitive knowledge among students aged 6–8 was related to more knowledge about problem-solving and improved learning.

The Present Research

The purpose of the present research was to examine the relationship among self-reported metacognition, attitudes about an outdoor learning program, and field-based learning in an environmental education program. Previous research has not examined the relationship of metacognitive knowledge to field-based learning in an environmental education setting. Questions also arise from a developmental perspective whether students in grades 3 and 5 possess the metacognitive knowledge and skills to support learning. The main research question was whether knowledge and regulation of cognition scores were related to attitudes and learning before and after completing a half-day field-based science curriculum. We measured metacognitive knowledge among students in the 4th and 5th grades in their daily classroom setting prior to a field-based learning experience using the Jr. MAI. We also measured attitudes about the experience before and after their participation, as well as pre- and posttest knowledge given the day long science intervention using assessments developed by the authors.

We made five predictions. Our first prediction was that the Jr. MAI would yield two reliable factors corresponding to knowledge of cognition (KOC) and regulation of cognition (ROC) scores. We expected these factors to explain approximately

35% of total sample variation, consistent with Sperling et al. (2002). Our second prediction was that the knowledge and regulation of cognition factors would be correlated in the .35 range, consistent with Sperling et al. (2002). Our third prediction was that there would be a significant increase from pretest to posttest attitudes as a result of the Forever Earth intervention. Fourth, we predicted that there would be a significant increase from pretest to posttest knowledge scores as a result of the Forever Earth intervention. Our fifth prediction was that KOC and ROC would be correlated with posttest knowledge scores. We expected students with higher self-reported metacognitive knowledge to score higher on the posttest knowledge assessment.

Methods

Participants

One hundred and thirty-four 4th and 5th grade students from a large school district in the Southwestern United States participated in the study. All 134 students completed the Jr. MAI, pretest attitudes, and pretest knowledge test in their classrooms approximately 3 weeks prior to the Forever Earth learning experience. Two 4th grade classrooms ($N=53$) and two 5th grade classrooms ($N=52$) visited the floating laboratory and completed the intervention which resulted in posttest attitude and knowledge scores.

The Forever Earth Learning Program

The Forever Earth program was brought about through the efforts of numerous partners including Forever Resorts, a division of Forever Learning, LLC; the National Park Service; Lake Mead National Recreation Area; Outside Las Vegas Foundation; and UNLV's Public Lands Institute. In 2005, a formal written agreement was reached between Fun Country Marine Industries and UNLV's Public Lands Institute to operate and manage the Forever Earth vessel for the purpose of enhancing outdoor environmental education efforts in Southern Nevada.

A development team consisting of science educators from the school district and educators from UNLV's Public Lands Institute (PLI) and Lake Mead National Recreation Area was formed to create the Forever Earth curriculum. The four member *On-Site Experience Development Team* consisted of program staff from the PLI and Lake Mead National Recreation Area. This team created the programming that was delivered aboard the Forever Earth vessel and on land at Lake Mead National Recreation Area and focused on creating engaging activities and ensuring that the mission and vision of the National Park Service and Lake Mead National Recreation

Area were accurately presented. The *Classroom Experience Development Team* authored the pre-visit and post-visit lessons. This team, consisting of four members (two from PLI and two from the school district), ensured that grade-appropriate science standards were met and that the science educator's perspective was carefully considered.

The curriculum for each grade level was developed to complement traditional classroom studies in grades four through seven with engaging, participatory, on-site activities and support lessons based upon a solid framework for inquiry and discovery. In the present study, 4th and 5th grade students participated in activities, performed investigations, and used scientific equipment to discover the answers to key questions while on the Forever Earth vessel (i.e., floating classroom and research laboratory).

Curriculum and Materials Used in the Research

Participants in Forever Earth programs explored the Lake Mead aquatic environment and its interrelationships with the surrounding area through their participation in two different curricula. Students in 4th grade completed the *The Water Cycle!* Curriculum in which they learned about Lake Mead's water use cycle by following one drop of water and then diagramming this important cycle on a magnet board. Working as scientists, students determined if water is the same in all parts of the lake by comparing water samples from the middle of the lake and from Las Vegas Bay.

Students in 5th grade completed the *Finicky Fish Finish Last!* Curriculum in which they explored what has happened to the Colorado River and the reasons why it is so difficult for a native fish species, the razorback sucker, to thrive in this changed environment. Students collected water quality data to determine whether habitat conditions are sufficient for the survival of young razorback suckers.

Two different types of student assessments were completed, including attitude and knowledge pre- and posttests.

Attitude Items

Two types of attitudes were assessed. The first included four questions administered prior to the Forever Earth intervention and immediately after the intervention that addressed attitudes about participating in the FE program, which we refer to as *intervention attitudes* because they focus on attitudes about the Forever Earth intervention before and after their participation. These questions are included as questions 1–4 in Appendix 1. The second type of attitudes addressed the extent to which participants felt they learned important information during the Forever Earth intervention, which we refer to as *learning attitudes* because they focus on the student's attitudes about his or her learning during the intervention. The questions are included as questions 5–8 of Appendix 2. Both questionnaires were developed for this research based on assessments used by (Metzger and McEwen 1999).

Knowledge Items

Assessments for each of the 4th and 5th grade curricula included four to five knowledge questions related to the specific activity. The 4th grade curriculum focused on *the water cycle* while the fifth grade focused on *native fish.* These knowledge questions consisted of constructed response items, where students were required to generate answers in response to a prompt rather than choose from a set of alternatives. Knowledge questions were developed to assess the instructional objectives outlined in each of the curricula. For example, one of the stated knowledge objectives for Water Cycle curriculum was "Students will identify how water in Las Vegas wash differs from water in Lake Mead." The corresponding knowledge item on the pre- and posttest was *How is the water from Las Vegas Wash different from water in the middle of Lake Mead?* Developing items for each knowledge objective help to ensure content validity of the assessment. See Appendix 3 for an example of the 4th grade knowledge assessment.

Procedures

The assessments were conducted over a 3-week period (i.e., pre- and post-intervention) to determine the effectiveness of the curriculum in having an impact on student attitudes and knowledge about the environment related to the curriculum content at each grade level. Pretests occurred one week prior to the study during a pre-intervention visit from the project facilitator for the FE intervention program. Students completed the pretests attitudes and knowledge scales as well as the Jr. MAI.

The curriculum was implemented on four separate occasions in December, 2008, involving 103 students from four schools. Two 4th grade classes and two 5th grade classes participated. All participants completed the attitude and knowledge assessments after the half-day curriculum on the Forever Earth vessel.

Procedures were identical for the four groups with the exception that content differed for 4th and 5th grade students. Students arrived at the Forever Earth vessel via school bus. They participated in a powerPoint introduction to the day's content (i.e., water cycle/finicky fish). The facilitator discussed activities, answered questions, and provided relevant background knowledge to students. Students then were given a research question (4th grade: Is the water in the middle of Lake Mead the same as the water in the Las Vegas wash) that served as a guide for the upcoming activities. Hands-on water measurements were made to answer the question posed to students by the facilitator. The central research question was answered by the whole group as part of collaborative discussion and inquiry. The final activity was to review the content and apply the knowledge to a real-life situation (e.g., ways the student can decrease water usage). Following these activities, students completed posttest attitude and knowledge scales, were debriefed, and returned to their school via bus.

Scoring

Scoring was completed by two of the authors who have extensive training in the scoring process. Constructed responses were scored as a 2, 1, or 0. Scores of 2 corresponded to more complete answers (see Appendix 3 for examples). Scores of 1 corresponded to partial answers. Scores of 0 corresponded to no answer or incorrect responses. The scores evaluated each knowledge protocol concurrently and resolved any differences during the scoring process, referring when necessary to a detailed scoring guide prepared prior to the study (see Appendix 3 for examples). The two scorers reached 100% percent agreement on all knowledge protocols.

Results

Four different types of data analyses were conducted. The first examined means and standard deviations for each critical variable at each grade level. Scores in Table 4.2 are based on composite scores using four pretest intervention attitude questions, four posttest intervention questions, four posttest learning questions, the 12 items from the Jr. MAI, four pretest knowledge questions, and four posttest knowledge questions that ranged from 0 to 8. The second set of analyses included several exploratory factor analyses with different rotations to examine the latent structure of the Jr. MAI. The third set consisted of correlations among critical variables. The fourth set of analyses examined dependent *t*-tests between posttest and pretest scores for attitudes and knowledge. These tests assessed whether there was significant change attributable to the Forever Earth curriculum.

Factor Analyses

A variety of exploratory solutions were used to examine the factor structure of the Jr. MAI. Consistent with Sperling et al. (2002), the most parsimonious solution

Table 4.2 Means and standard deviations for 4th and 5th grade variables

	4th grade		5th grade	
Variable	Mean	SD		
Pretest attitudes	16.40	2.51	16.12	2.70
Posttest attitudes	17.79	2.50	18.78	1.76
Intervention attitudes	17.44	2.75	18.52	1.78
Knowledge of cognition	21.22	2.65	20.83	2.92
Regulation of cognition	26.13	4.98	25.80	4.39
Pretest knowledge	2.58	1.32	1.84	1.00
Posttest knowledge	4.68	1.39	4.90	1.97

Table 4.3 Factor loadings, eigenvalues, and scale reliabilities

Item	Factor 1	Factor 2	Eigenvalue
Knowledge of cognition			
I can make myself learn when I need to		.74	
I learn best when I already know something about the topic		.72	
I really pay attention to important information		.55	
I know when I understand something		.53	
I know what the teacher expects me to learn		.40	1.46
Regulation of cognition			
When I am done with my schoolwork, I ask myself if I learned what I wanted to learn	.73		
I think of several ways to solve a problem and then choose the best one	.64		
I think about what I need to learn before I start working	.63		
I try to use ways of studying that have worked for me before	.62		
I draw pictures or diagrams to help me understand while learning	.47		
I ask myself how well I am doing while I am learning something new	.44		
I learn more when I am interested in the topic	.36		3.05

consisted of a principal components extraction with a varimax rotation (see Table 4.3). This analysis yielded two factors which explained 35% of the total sample variation. Factor 1 corresponded to the regulation of cognition factor described earlier and explained 25% of sample variation with an eigenvalue of 3.05. The regulation factor included seven items and was reliable at .78 using Cronbach's alpha. Item 7 (i.e., When I am done with my schoolwork, I ask myself if I learned what I wanted to learn) had the highest item-to-factor loading at .73. The regulation of cognition variable included items that focused on skills and strategies such as checking and monitoring that enable effective learners to regulate their learning. Factor 2 corresponded to the knowledge of cognition factor described earlier and explained an additional 12% of total sample variation with an eigenvalue of 1.46. The knowledge factor included five items and was reliable at .68 using Cronbach's alpha. Item 1 (i.e., I can make myself learn when I need to) had the highest item-to-factor loading at .74. The knowledge of cognition variable included items that focused on declarative, procedural, and conditional knowledge such as understanding optimal study conditions that facilitate effective learning.

The two-factor solution is quite consistent with our hypothesized factor structure and the empirical results reported by Sperling et al. (2002), who found two factors that explained 35% of sample variation. Sperling et al. (2002) reported similar item-to-factor loadings with the exception of item 12 (i.e., I learn more when I am interested in the topic), which loaded on the regulation of cognition factor in the present study rather than the knowledge of cognition factor.

Table 4.4 Correlations

	Pretest Int. attitudes	Posttest Int. attitudes	Learning attitudes	KOC	ROC	Pretest know	Posttest know
Pretest intervention attitudes		.69**	.58**	.38**	.09	.36**	.23*
Posttest intervention attitudes	.54**		.76**	.44**	.10	.22	.30*
Learning attitudes	.37**	.63**		.41**	.04	.44**	.36**
Knowledge of cognition	.54**	.41**	.45**		.38**	.14	.23*
Regulation of cognition	.56**	.50**	.31*	.39**		.06	.25*
Pretest knowledge	.06	.31*	.10	.10	.05		.53**
Posttest knowledge	.16	.38**	.32*	.24*	.39**	.13	

Note: 4th grade correlations appear above the main diagonal; 5th grade correlations appear below
*$p < .05$; **$p < .01$

Correlations

Correlations between all critical variables are shown in Table 4.4. Correlations using the 4th grade data are shown above the main diagonal; whereas correlations using 5th grade data are shown below the main diagonal. All tests of significance were made using a one-tail directional test in which correlations were expected to be positive and significantly different from the null hypothesis of zero correlation.

Three results were of special importance. The first is that all variables are correlated significantly with the posttest knowledge scores. This finding suggests that positive attitudes and both metacognitive factors are related positively to performance on the knowledge posttest. This finding is consistent with the data reported by Sperling et al. (2002) in with the Jr. MAI was correlated significantly with strategic knowledge, problem-solving, and academic achievement. Our second finding was that the knowledge and regulation of cognition factors were correlated, .38 and .39, respectively. This suggested that the knowledge and regulation aspects of metacognition are related to a moderate extent, which is consistent with the correlation of .35 reported by Sperling et al. (2002), as well as the .50 correlation reported by Schraw and Dennison (1994) using the MAI. Our third finding is that all variables were correlated positively and significantly with the knowledge of cognition factor; whereas variables at the 4th grade were not correlated with the regulation of cognition factor. This finding suggested that knowledge about oneself as a learner is related to attitudes and performance more strongly than self-regulatory aspects of metacognition.

Overall, the correlations shown in Table 4.4 indicated that the knowledge and regulation of cognition variables were correlated with themselves and other variables in the predicted direction and relative size of the correlation. Our findings were quite similar to Sperling et al. (2002) and Schraw and Dennison (1994). These findings strongly supported the concurrent and predictive validity of the Jr. MAI in that it was correlated significantly with attitudes and a future test of knowledge.

Table 4.5 Attitude and knowledge change scores by grade level

	Sample size	Mean	Standard deviation	*t*-Value	Significance
Grade					
4th					
Intervention attitude change score	53	1.18	1.97	4.16	.001
Knowledge change score	53	2.09	1.32	11.56	.001
5th					
Intervention attitude change score	52	2.69	2.32	8.04	.001
Knowledge change score	52	3.06	2.90	10.59	.001

Attitude and Knowledge Scores

Table 4.5 shown the means and standard deviations based on the difference between post-intervention and pre-intervention attitude and knowledge scores. Both the attitude, $t\ (52) = 4.16$, $p < .001$, and knowledge scores, $t\ (52) = 11.56$, $p < .001$, were highly significant at the 4th grade. These results were replicated at the 5th grade as well, where both the attitude, $t\ (51) = 8.04$, $p < .001$, and knowledge scores, $t\ (52) = 10.59$, $p < .001$, were highly significant. These findings revealed that the Forever Earth intervention significantly increased attitudes and knowledge from pretest to posttest. In addition, the learning attitudes scale differed significantly from zero at the 4th, $t\ (52) = 44.34$, $p < .001$, and 5th grades, $t\ (51) = 74.27$, $p < .001$.

A comparison of effect sizes indicated that the differences between pre- and posttest were quite robust. The differences for the pre- versus posttest attitudes ranged from .50 to 1.00, which are considered moderate to large effect sizes. The differences for the pre- versus posttest knowledge scores ranged from 1.0 to 1.60, which are considered large. Collectively, these effect sizes revealed that the Forever Earth intervention produced large post-intervention gains among students.

Discussion

The main goal of the present research was to examine the relationship among self-reported metacognition, attitudes about an outdoor learning program, and field-based learning in an environmental education program. We made five predictions about the factor structure of the Jr. MAI, the relationship between the two hypothesized factors, and their relationships to other variables. In addition, we predicted that the Forever Earth intervention would lead to significant increases in student attitudes and knowledge.

Our first prediction was that the Jr. MAI would yield two reliable factors corresponding to knowledge of cognition (KOC) and regulation of cognition (ROC) constructs described by Schraw and Dennison (1994) and Sperling et al. (2002). We expected these factors to explain approximately 35% of total sample variation, consistent with Sperling et al. (2002). A principal components analysis with varimax rotation yielded two factors that corresponded very closely to the hypothesized factors. Together, the two factors explained 35% of sample variation and were reliable using Cronbach's alpha. These findings replicated Sperling et al. (2002) and suggest that the knowledge and regulation of cognition factors are consistent across younger and older students and that these constructs can be measured in a reliable and valid manner.

Our second prediction was that the KOC and ROC factors would be correlated in the .35 range, consistent with Sperling et al. (2002). Data from 4th grade students revealed a correlation of .39 while data from 5th grade students found a correlation of .38. These values were very close to those reported by Sperling et al. (2002) and similar to values reported by Schraw and Dennison (1994) using the MAI. Collectively, these findings suggest that knowledge of cognition and regulation of cognition factors are correlated moderately. Indeed, previous research suggests that the two factors most likely co-develop as children become more metacognitively aware (Annevirta and Vaurus 2006).

Our third prediction was that there would be a significant increase from pretest to posttest attitudes as a result of the Forever Earth intervention. Pretest attitudes increased significantly at both 4th and 5th grades due to the intervention (see Table 4.2). This result indicated that students enjoyed the floating laboratory experience and would be willing to participate again. In particular, the composite mean for posttest attitudes for 4th (17.79) and 5th (18.78) grades using a 20-point scale revealed very highly favorable ratings. In addition, ratings for posttest learning attitudes for 4th (17.44) and 5th (18.52) grades using a 20-point scale revealed very favorable ratings about the degree of learning due to the Forever Earth intervention.

Our fourth prediction was that there would be a significant increase from pretest to posttest knowledge scores as a result of the Forever Earth intervention. Knowledge gain scores increased significantly at both 4th and 5th grades due to the intervention (see Table 4.5).

Our final prediction was that knowledge of cognition and regulation of cognition scores would be correlated with posttest knowledge scores. We expected students with higher self-reported metacognitive knowledge to score higher on the posttest knowledge assessment. Correlational data from Table 4.4 supported this claim, indicating that students who reported higher levels of knowledge and regulation of cognition scored higher on the knowledge posttest. Table 4.4 also reveals that knowledge and regulation scores were not correlated with pretest knowledge scores. This suggested that the gains in knowledge due to the Forever Earth intervention were related, in part, to the use of metacognitive knowledge to help students identify important information and learn that information more effectively.

The results of the present study support three main conclusions. The first is that the Jr. MAI assessed the knowledge and regulation of cognition factors in a reliable and valid manner. The factor analyses supported the claim that the 12 items on the Jr. MAI assess appropriate types of metacognitive knowledge. The correlations with other variables such as posttest attitudes and knowledge scores supported the predictive validity of the Jr. MAI in that KOC and ROC scores predicted future performance significantly.

A second conclusion is that metacognitive knowledge is related positively to increases learning and attitude change (Efklides 2008). One explanation is that students with higher levels of metacognition are more aware of what is important to learn and what strategies to use to learn this information (Pressley and Harris 2006). These students are better able to select information, organize, and elaborate critical information into an integrated conceptual understanding of the material. Indeed, this argument was supported by the positive correlation between metacognition and posttest knowledge scores. In addition, metacognition may enhance the value of learning, make the information more interesting, and increase students' satisfaction with the learning experience.

This finding is important as well from a developmental perspective. Previous research suggests that metacognition is late developing (i.e., age 11 and older) and that younger students, especially those in grades 1–6, usually possess limited metacognitive skills (Kuhn 2000). Nevertheless, research indicates that younger students benefit from metacognitive instruction as early as grade 1 (Blank 2000; Annevirta and Vaurus 2006). Metacognition appears to develop faster due to direct instruction, dialogue and reciprocal discussion, and collaboration and peer assistance (Pressley and Harris 2006). Our findings support the claim that a field-based program that includes interactive instructional opportunities such as dialogue, exploration, and peer assistance may show a significant relationship between metacognition and learning.

A third conclusion is that the Forever Earth intervention leads to significant gains in attitudes about the program, about learning, and knowledge. There are several reasons for the growth observed in the present study. One is that many of the students have relatively little knowledge of the curriculum prior to their participation in Forever Earth. A second reason is that the curriculum they encounter during the floating laboratory experience is developmentally appropriate and linked to current grade-level science instruction. This makes the information relevant to ongoing science instruction in the classroom. A third reason is that the Forever Earth program capitalizes on real-life, hands-on science learning that strongly engages younger students from both cognitive and motivational perspectives.

We believe our findings shed light on the importance of metacognitive knowledge in nonschool settings. Like the school classroom, the Forever Earth experience used a structured curriculum to enhance student learning. However, it differed from a traditional classroom in that it was low stakes, hands on, experiential, and based in a novel setting. All of these new characteristics of the learning environment probably

required students to use a broader array of metacognitive skills than a traditional classroom learning experience. It is our assumption that students faced more conditional knowledge demands due to the new learning environment and engaged in more self-monitoring than in typical classroom settings. We also assume that students were more motivated (based on attitude data) to use their existing metacognitive skills than they might have been in a traditional classroom. It may be the case that students would not have applied their metacognitive knowledge to the same degree to classroom learning. We believe that future research should compare the role of metacognitive knowledge inside and outside the classroom using the same students to test this possibility.

Educational Implications

Consistent with a number of previous studies, the present research highlights the importance of promoting metacognition in science learning (Linn and Bat-Sheva 2006). There are at least four related instructional strategies that educators might use to promote metacognitive awareness based on previous instructional research. Although these strategies have been studied primarily in traditional classroom settings, we believe they can be taught and used effectively in a variety of settings such as the field-based experiences described above. One is to assess students' metacognitive knowledge and self-regulatory skills prior to instruction. Students with more metacognitive awareness find it easier to learn and remember. Students who report low metacognitive knowledge may benefit from explicit instruction and collaborating with a more experienced learner.

A second way to improve learning is to activate metacognitive skills through pre-learning activities such as brainstorming and group discussion. Pre-learning activities can activate relevant background knowledge and remind students to use cognitive and metacognitive skills in their learning repertoire. Inquiry methods also can be an especially effective way to activate strategies and relevant metacognitive knowledge (Chinn and Hmelo-Silver 2002). Inquiry teaching promotes self-regulation in two ways. One is to stimulate active engagement in the learning process by using cognitive learning strategies and metacognitive strategies to monitor their understanding. A second is to help increase motivation to succeed in science by using modeling, active investigation such as predict-observe-explain (POE) (Windschitl 2002), or question asking.

A third approach to improving learning is to help students develop and refine metacognitive knowledge and regulatory skills. Zohar (2006) reported that explicit metacognitive instruction improved strategy use, problem-solving, and learning in older students. Schraw (2001) proposed the use of a strategy evaluation matrix in classroom or field-based settings in which students collectively discuss different learning strategies as well as how, when, and why to use them to improve

learning. This method provides explicit discussion and reflection on key learning strategies. Schraw (2006) also proposed the use of a metacognitive checklist to be used during learning to plan, monitor, and evaluate one's learning in a systematic way.

A fourth approach is to promote metacognitive knowledge and regulation through active reflection and dialogue. Blank (2000) proposed a model of critical thinking in science called the *metacognitive learning cycle* (MLC). The MLC emphasizes the systematic use of discussions and reflection to promote explicit metacognitive understanding of critical thinking and problem-solving. The MLC consists of four interrelated steps, which include concept introduction, concept application, concept assessment, and concept exploration. Students were asked to reflect upon their progress at each step either individually or in small groups. In comparison with groups that did not use explicit reflection, the MLC experienced greater conceptual restructuring and understanding of course content.

Taken collectively, these strategies are well known to facilitate metacognitive knowledge and skills in a manner that promotes science learning (Linn and Bat-Sheva 2006). Blank (2000) also has argued that metacognitive skills are learned better when encountered within highly contextualized science learning experiences. We believe that the Forever Earth program provided specific learning goals and content for students in a supportive learning context that enabled them to use their metacognitive knowledge and skills in an optimal fashion and to share their skills collaboratively with other students.

Conclusions

The goal of this chapter was to provide an overview of metacognition and present data that link different types of metacognitive knowledge to attitudes and knowledge scores in a field-based science learning experience administered to 4th and 5th grade students. We administered the Jr. MAI and extracted knowledge of cognition and regulation of cognition factors. These factors were positively related to attitudes and posttest knowledge scores. The knowledge and regulation factors also were significantly related to each other. The half-day Forever Earth program produced large effect size gains for both attitudes and knowledge. Together, these results suggested that metacognitive knowledge is an important component of science learning and is related to higher attitude and knowledge scores. We concluded with several suggestions for improving metacognitive knowledge in younger students.

Appendix 1

The Jr. MAI adapted from Sperling et al. (2002)

How I Study

We are interested in what students do when they study. Please read the following sentences and circle the answer that describes you and the way you are when you are doing school work or home work. There are no right answers – please describe yourself as you are, not how you want to be or think you ought to be.

		1 = never	*2 = seldom*	*3 = sometimes*	*4 = often*	*5 = always*
1.	I know when I understand something.	1	2	3	4	5
2.	I can make myself learn when I need to.	1	2	3	4	5
3.	I try to use ways of studying that have worked for me before.	1	2	3	4	5
4.	I know what the teacher expects me to learn.	1	2	3	4	5
5.	I learn best when I already know something about the topic.	1	2	3	4	5
6.	I draw pictures or diagrams to help me understand while learning.	1	2	3	4	5
7.	When I am done with my schoolwork, I ask myself if I learned what I wanted to learn.	1	2	3	4	5
8.	I think of several ways to solve a problem and then choose the best one.	1	2	3	4	5
9.	I think about what I need to learn before I start working.	1	2	3	4	5
10.	I ask myself how well I am doing while I am learning something new.	1	2	3	4	5
11.	I really pay attention to important information.	1	2	3	4	5
12.	I learn more when I am interested in the topic.	1	2	3	4	5

Appendix 2

Attitude Questionnaire

1. I would tell my friends to do this program on the Forever Earth Floating Classroom.

Strongly agree	Agree	Not sure	Disagree	Strongly disagree
5	4	3	2	1

2. Learning about water at Lake Mead was very interesting to me.

Strongly agree	Agree	Not sure	Disagree	Strongly disagree
5	4	3	2	1

3. The forever Earth activities were fun.

Strongly agree	Agree	Not sure	Disagree	Strongly disagree
5	4	3	2	1

4. I would like to do another Forever Earth program.

Strongly agree	Agree	Not sure	Disagree	Strongly disagree
5	4	3	2	1

5. I learned how important Lake Mead is to plants, animals, and people.

Strongly agree	Agree	Not sure	Disagree	Strongly disagree
5	4	3	2	1

6. I learned important things today about the water.

Strongly agree	Agree	Not sure	Disagree	Strongly disagree
5	4	3	2	1

7. I learned how people can use Lake Mead without hurting it.

Strongly agree	Agree	Not sure	Disagree	Strongly disagree
5	4	3	2	1

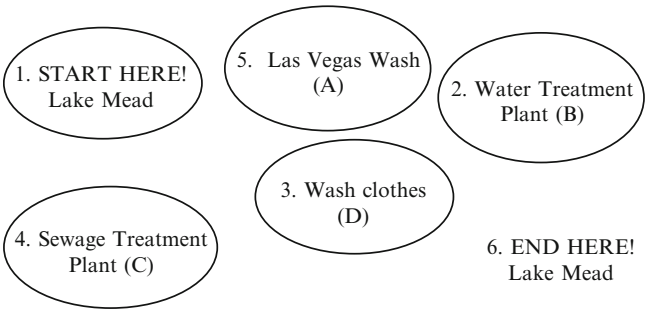
8. Because of what I learned today, I think it's important to take care of Lake Mead.

Strongly agree	Agree	Not sure	Disagree	Strongly disagree
5	4	3	2	1

Appendix 3

Fourth Grade Assessment Items and Scoring Guide

1. Describe what happens when Lake Mead's water is used by people by putting these steps in order from 1 to 6. Write the number on the line in each circle.



More complete: 2 points

- Response has 3–4 items in the correct order

Partial complete: 1 point

- Response has 1–2 items in the correct order

Less complete: 0 points

- Response has no items in the correct order

2. How is the water from Las Vegas Wash different from water already in the lake? Answer "yes" or "no" to the following questions.

   – Yes Would one water sample be clearer than the other sample?
   – No Would the plankton be different?

More complete: 2 points

- Response has both items answered correctly

Partial complete: 1 point

- Response has one item answered correctly

Less Complete: 0 points

- Response has neither item answered correctly

3. List some of the reasons why the water is so low in Lake Mead.
   More complete: 2 points
   - Response has 2 correct responses and no more than 1 incorrect answer
     - People have used the water for different things
     - Evaporation
     - Drought

   Partial complete: 1 point
   - Response must include one correct positive item

   Less complete: 0 points
   - Response does not include any correct items
     - The dam has a leak
     - Pollution

4. What can you do to save and protect the water in Lake Mead?

   More complete: 2 points
   - Response includes two correct answers
     - Take shorter showers
     - Turn off the tap when brushing teeth
     - Don't litter
     - Only use what you need
     - Use less water
     - Recycle

   Partial complete: 1 point
   - Response includes one correct answer or one less-specific answer
     - Don't waste water

   Less complete: 0 points
   - No information or incorrect information provided

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Chapter 5
The Role of Metacognition in Students' Understanding and Transfer of Explanatory Structures in Science

Tina Grotzer and Sarah Mittlefehldt

Introduction

The ability to mentally "step back" and manage how one thinks about and interacts with the world opens up new possibilities for learning and behavior. Reflective capacity moves us beyond merely acting, and reflection at different levels enables new insights, learning, and ability to act in more effective ways in the future. This chapter examines how students' metacognition relates to the likelihood that they will consider their assumptions about the causal structures embedded in scientific explanations and how this correlates with understanding and transfer of the concepts.

Research shows that students tend to use reductive default patterns (Feltovich et al. 1993) in reasoning about science (e.g., Chi 2005; Driver et al. 1985; Grotzer 1993; Grotzer and Basca 2003; Hmelo-Silver et al. 2007; Perkins and Grotzer 2005; Resnick 1994). For instance, they often use a different ontological category—using substance or matter-oriented explanations when process-oriented explanations are warranted (Chi 1992). Or they expect obvious causes and obvious effects, miss effects that involve systems in equilibrium, or those that involve "passive" agents (Grotzer 2004). They assume simple linear, sequential causal patterns with temporal priority between causes and effects (Bullock et al. 1982; Grotzer 1993).

Many science concepts, symbiosis, pressure or density differentials, and electrical circuits, are nonlinear in form involving mutual, relational, or cyclic patterns. They may entail other forms of causal complexity—non-obvious causes; time delays

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and spatial gaps between causes and effects; distributed, unintentional agency; and probabilistic causation where the level of correspondence between causes and effects varies. These forms of complexity are pervasive—part of ecosystem dynamics, global warming, interdependent economies and so forth. Preparing learners to live in a complex world requires helping them learn to be metacognitive about and to reason about such explanatory structures.

Students are typically unaware of their reductive assumptions, and these structural patterns are not addressed by most science curriculum. When extraneous task demands are controlled, even young children can handle some causal complexity (e.g., Kushnir and Gopnik 2007; Sobel 2004). However, causal learning is often implicit, efficient, and subject to the limits of our attention at the moment. In order to move beyond these default assumptions, higher order reflection on the explanatory structure may be needed. Engaging students in activities and discussion designed to reveal the nature of the underlying structure has met with some success in helping students develop deeper understandings of fundamental concepts (e.g., Grotzer and Basca 2003; Perkins and Grotzer 2005).

The Role of Metacognition in Addressing Reductive Assumptions and Encouraging Transfer

A substantial body of research underscores the power of metacognition for enhancing student learning in science. Students who are more metacognitive in their behaviors tend to perform better (e.g., Anderson and Nashon 2006), and when students become more metacognitive, their learning improves (e.g., Baird 1986). Engaging students in metacognitive reflection improves learning in science (e.g., White and Frederiksen 1998, 2000) and beyond (e.g., King 1994; Mevarech 1999; Paris and Jacobs 1984) and results in more permanent restructuring of science ideas (Blank 2000) so that students are less likely to lapse back to earlier, less scientifically accepted ideas. Further, engaging students in metacognition improves the performance of the lowest level achievers the most by helping them manage their thinking (White and Frederiksen 1998, 2000), offering a window into the thinking of peers, by unpacking the structure of the concepts being learned (Perkins and Grotzer 2005), and helping them to learn metastrategic knowledge (Zohar and David 2008; Zohar and Peled 2008). In the study below, we examined whether metacognition might help students to recognize their reductive biases, learn the science more deeply, and transfer it more readily.

Zohar and colleagues (Zohar and David 2008; Zohar and Peled 2008) include the ability to analyze causal relationships as a form of metastrategic knowledge. Metastrategic knowledge refers to "general knowledge about cognitive procedures that constitute higher order thinking skills" (Zohar and Peled 2008, p. 338). In order to effectively deploy particular strategies in particular instances of causation, one first needs an awareness of types of causal patterns and causal features. What is called for is a meta-structural knowledge—the ability to reflect upon and recognize particular forms of causal patterns. It involves detecting the features that

make up particular patterns as well as how some of those features make them difficult to detect and to reason about given our human perceptual apparatus. Getting students to reflect upon their causal assumptions and to recognize that they are structuring their explanations in specific ways may be an important step in addressing them.

Most definitions of metacognition include an awareness of cognition as an essential aspect—including both the content of one's own thinking and of one's conceptions (Baird 1986; Hennessey 1999; Kuhn et al. 1988). Hennessey (1999) included active monitoring and attempts to regulate one's cognitive processes toward the goal of furthering learning. Schraw and colleagues (e.g., Schraw 1998; Schraw et al. 2006) focus on knowledge of cognition and the regulation of cognition. They include procedural knowledge, such as note-taking, knowing to slow down for difficult information, etc., as well as conditional knowledge about why or when to use a particular strategy. Evaluation has been key to many definitions (e.g., White 1992). Anderson and Nashon (2006) recently distilled the research to six key dimensions: awareness, control, evaluation, planning, monitoring, and self-efficacy.

Awareness, monitoring, and evaluation (Anderson and Nashon 2006) are perhaps the most critical in realizing one's causal default assumptions and the impact that they have on understanding science concepts. Awareness enables us to detect difficulties in understanding science concepts and to realize how one's default assumptions can distort concepts being taught. Actively monitoring how these assumptions interact with one's science conceptions is critical to transferring understanding beyond the contexts taught and to the real world. Evaluation can play a critical role in choosing the most effective causal framing as students structure new concepts particularly in a conceptual change framework where one is evaluating explanations against the available evidence and trading up for the most powerful explanatory model.

Research (Blank 2000; Georghiades 2000; Hogan 1999; Nickerson et al. 1985) has demonstrated the importance of mental management, or metacognition, as a means to support the restructuring of ideas in science. Metacognitive questions at the intersection of self-awareness and task and/or concept knowledge have been used by others to encourage students to regulate their learning processes in the service of further learning and deep understanding (Beeth 1998a; Blank 2000).

Metacognition should also enhance transfer of concepts. Metacognitive activities engender deeper, more flexible understandings because they are more deeply and actively processed, and these deeper understandings in turn result in more durable or robust concepts which are more readily available for transfer (Blank 2000; Georghiades 2000; Hogan 1999). Blank (2000) included metacognitive "status checks" in terms of how sensible and plausible ideas were as part of a "Metacognitive Learning Cycle" (MLC). She found that classes that used the MLC did not gain a greater pool of content knowledge. However, toward the end of the school year in May, students in these classes revealed significantly greater retention of content.

Perkins and Salomon (1988) distinguish between low road and high road transfer. Low road transfer is reflexive in character—the features of the problem space invite transfer with automaticity (such as driving a mower and a car.) However, the successful mapping and transfer of science concepts to new contexts requires high

road transfer—where the learner actively evaluates the fit of the explanatory model and whether it provides a powerful explanation in the given instance.

In earlier work, we engaged students in reflecting upon the nature of the embedded causality in the science that they were learning (e.g., Grotzer and Basca 2003; Perkins and Grotzer 2005). Through activities and discussion designed to reflect upon the embedded causality, students considered the implicit causal structure of the concepts. Awareness of the causal structure was guided primarily by the teacher. The current study attempts to shift responsibility for these reflective behaviors to the students with the hope that it would increase the likelihood of student-initiated transfer.

Three dimensions and related questions were used to frame the metacognitive aspects of the study:

1. Intelligibility: Does the explanation make sense to me?
2. Plausibility: Do I think that the explanation is a possible explanation?
3. Wide-applicability: Can I apply the explanation beyond the contexts in which I have learned it?

These were intended to encourage a focus on one's own thinking, a shift in ownership for learning, and to potentially increase the likelihood of transfer as students were learning about causal patterns in density and air pressure. The first two dimensions were adopted from the teaching of Sister Gertrude Hennessey and written about by Beeth (1998a).

Intelligibility encompasses how students reflect on the sense that their concepts make, as they ask, "Does this make sense to me?" It invites self-initiated *awareness* of their sense-making process and offers a conceptual foundation in which to activate their metacognitive processes. Intelligibility also invites *monitoring* of one's sense-making processes. Too often, students assume that the ideas must make sense to someone—the teacher or other students—but do not actively reflect on whether or not the ideas make sense to them. Assessing the intelligibility of a new idea can also include an interpersonal dimension in addition to an intrapersonal dimension. Students may be encouraged to reflect on other students' ideas, their parents' ideas, or the teachers' ideas. They may learn to ask themselves, "How does the way that this person thinks about the idea help me make sense of it?" However, questions of intelligibility necessarily invite awareness of one's own sense-making.

Plausibility enables students to test their faith in a particular idea vis-à-vis alternative ideas. It is the realm in which students negotiate the status of their ideas, and it invites *evaluation* of the ideas and one's belief in the ideas in terms of their explanatory value. It encompasses the type of metacognition that occurs when students ask themselves, "Should I really believe this idea?" When testing the plausibility of an idea, students may seek counter-evidence against an idea. Students focused on plausibility are often very self-aware of their learning. As a result, they may question the learning and be skeptical of ideas that they only partially understand. Intelligibility and plausibility are important components in deciding whether or not to own an explanation—believability. Ultimately, students need to ask not only

whether something is sensible and plausible but whether or not they personally believe it. Students can find an idea plausible but not actually believe it themselves particularly if they find another explanation to be more compelling. An interesting component of plausibility relates to students' recognition of changes in their own thinking, that is, when students say that they used to understand an idea one way and begin to think about the same idea in a different way after witnessing counter-evidence. Often in this case, students' initial ideas may be held simultaneously with the negotiation of new understandings. In this sense, the student assesses their understanding of an idea by comparing their faith in their initial ideas weighed against the new and developing ideas.

Both intelligibility and plausibility complement pedagogies that engage students in modeling. The epistemology of science involves thinking about the explanatory power of a model in terms of the available evidence (e.g., Giere 1988; Hestenes 1992), discarding models that no longer fit, and trading up for more powerful models (Kuhn 1962). Models are a natural extension of classroom discourse in teaching the epistemology of science. Debating and defending models render students' thinking visible (Lehrer and Schauble 2006) to the person espousing the model, other students, and the teacher. Evaluating models for their intelligibility and plausibility is an integral part of discussions in the classrooms studied.

"Wide-applicability" involves connection-making—asking "How can this concept help me in other areas of my learning?" or "What experiences (in class or outside of class) have I had that would help me make sense of this idea?" Wide-applicability is broader in its aims than "fruitfulness," defined by others as part of conceptual change (Beeth 1998b; Hewson and Hewson 1988). As argued by Georghiades (2006), application is only part of the process of transfer. Transfer includes the challenges defined by Gentner (1983)—sensing a structural similarity, mapping from target to base to assess that perceived similarity, deciding where the mapping fits and where it falls down, and actually applying a concept in instances where it is helpful. "Wide-applicability" involves this mapping of the concept against the dimensions of the problem context to figure out where it does and doesn't fit as well as examining its explanatory power beyond the confines of the classroom to understanding in the real world.

The set of three dimensions and framing questions leads to asking a more nuanced set of questions that pertain to both intra- and interpersonal contexts of examining cognition as outlined in Table 5.1. Focusing on these dimensions and asking related questions were referred to as making "metacognitive moves" with the students in the study described below.

The study explored how students responded to the introduction of "metacognitive moves" while learning about the nature of the causal patterns implicit in density and pressure-related concepts. We asked the following questions: (1) What evidence would we find for the types of approaches that students adopted and the ways in which they employed them? and (2) Would there be any evidence that these metacognitive moves may have facilitated transfer of causal understanding between science topics?

Table 5.1 Metacognitive moves: context and characteristic questions

Metacognitive dimension	Context	Characteristic questions
1. Intelligibility	Intrapersonal	Does this idea make sense to me?
		What part of this idea makes sense to me?
		What do I find difficult about this idea?
	Interpersonal	What part of Ian's model makes sense to me?
		What might I add to have it make sense to me?
2. Plausibility	Intrapersonal	Should I believe this idea?
		Does this idea seem likely to be true?
	Interpersonal	Should I believe Ian's model?
		Even if it makes sense to me, is there something about it that seems unlikely to be true?
		What is believable about it?
3. Wide-applicability	Intrapersonal	How can this idea help me in other areas of my learning ?
		Are there pieces of this idea that relate to other ideas I learned about?
		What are the fundamental ways in which they relate?
	Interpersonal	How does Ian's model help me think about other ideas we've talked about?

Infusing Metacognitive Moves in the Classroom

Design

In six eighth grade science classrooms, concepts related to the three dimensions of intelligibility, plausibility, and wide-applicability were infused into "best practices" in science curricula with a focus on using causal forms to deepen understanding for density and air pressure. The best practices included a focus on modeling, active construction of ideas, dynamic computer simulations, Socratic discussion, and being "minds-on." The units also included explicit instruction about the nature of the embedded complex causal forms as described in greater detail below. Each unit was 8 weeks long. The metacognitive support was both materials-based and teacher-facilitated, as described below, and designed to encourage deep learning and to result in greater transfer.

The existing curriculum already included activities designed to increase students' awareness of the underlying causality inherent in the concepts that they were learning. In each of the units, density and air pressure, students needed to grasp an underlying relational causality where a relationship between two things, either balance or differential, accounts for a certain outcome beyond the two things. The density unit incorporated relational causality to explain how density differentials cause something to sink or float, and the air pressure unit engaged students in thinking about pressure differentials involved in a variety of phenomena such as what causes lift, or what causes liquid to go into your mouth when you drink from a straw.

This involves a conceptual shift for most students—away from simple linear models ("It is dense so it sinks" or "I suck on the straw and pull the liquid to my lips") to a relational causal model ("The object is denser than the liquid so it sinks in this liquid—but could float in another" or "I create lower pressure in the straw creating an imbalance with the higher pressure outside the straw, so the liquid gets pushed up.").

All students also engaged in explicit discussion designed to help them grasp the underlying causal structures. This discussion unpacked the features of the underlying causality and considered how they differed from simpler models that students were likely to bring to their learning. Examples of the activity sheets that guided this discussion can be found in the appendices. The entire curriculum that was used as a basis for the unit for all students can be found at: http://pzweb.harvard.edu/ucp/. The activities and explicit discussion of causal structures and their features have been shown to significantly enhance students' understanding of the target concepts (e.g., Basca and Grotzer 2001; Grotzer 1993; Perkins and Grotzer 2005). Therefore, these components were held constant in the current study. These aspects of the intervention are, in a sense, metacognitive as they increase *awareness* of the underlying causality embedded in the concepts. As discussed above, awareness is key to realizing one's causal default assumptions and the impact that they have on understanding science concepts.

The metacognitive moves that were assessed in this study were designed to go beyond the teacher's encouragement of students' awareness through the activities and discussion. The moves were designed to shift ownership for the metacognitive components to encourage students to become more aware of their causal assumptions and to encourage greater monitoring and evaluation on behalf of the students. While the actual teaching of the metacognition was supported by materials-based and teacher-facilitated activities, the aim was to encourage students to extend the metacognitive techniques beyond these supports. The research conducted here considers, both qualitatively and quantitatively, metacognitive behaviors that students revealed, how these correlated with transfer of causal concepts, and the extent to which this shift in ownership took place.

Subjects: Students in six eighth grade classes ($n = 182$) participated. The school, in a suburb of Boston, serves primarily middle class families of Caucasian, Middle Eastern, and Indian ethnicities. The classes were taught by two science teachers with three classes of each teacher participating. Pre- and posttest data of students' understanding of science content with embedded causal complexity and metacognitive class level data were collected for all of the students. A subset of three students ($n = 18$) from each class, the primary focus of the results reported below, were interviewed following each unit to assess their understanding of the concepts and their metacognitive behavior. Their writing samples were analyzed in depth.

Class interactions were documented for later analysis of the metacognitive activity. Daily field notes were taken to record observations on in-class dynamics, including metacognitive discussions, the general mindfulness of the class, and major distractions to the class. Explicit teacher–student as well as student–student discussions on the status of ideas and other spontaneous instances of metacognitive activity in class were recorded on a daily basis.

Instructional Materials

The intervention included both materials-based and teacher-facilitated metacognitive support because we expected that teacher-facilitated support would lead to the most conducive classroom culture but recognized that, beyond the context of the investigation, more classrooms would be likely to have materials-based than teacher-facilitated support.

Materials-Based Metacognition

The teaching materials for the unit were infused with questions encouraging students to behave metacognitively. For example, when introduced to what causes differences in density, students were asked to think and write about the intelligibility ("Of what you've learned about what causes differences in density, what makes sense to you? Are there any pieces of what you've learned that seem especially clear to you? What doesn't make sense to you? What pieces seem especially difficult to understand?") (For further examples, see Appendix 1). In addition, posters with questions relevant to the three forms of metacognition were hung around the rooms.

Teacher-Facilitated Metacognition

The units also included explicit opportunities to engage in teacher-guided metacognition. For instance, while students were working on developing models in a group, their interactions were videotaped, and in a subsequent class, students were asked to reflect on what thinking moves they were using and how the moves supported their developing understanding. They also observed and reflected upon whole class videos. As they watched themselves discussing how objects (of different materials) with the same volume could have different masses, the teacher also encouraged students to consider the plausibility of ideas and to connect ideas to other areas of learning (see Appendix 2).

Assessment Tasks of Learning a Metacognitive Behavior

Density and Pressure Written Assessments

Students took a written inventory with ten questions. It included open-ended questions targeting specific difficulties that result in alternative conceptions (i.e., Show and explain the possible outcomes when an object is dropped into a liquid.). It also included multiple-choice questions with responses designed to match specific beliefs that students tend to have about density (i.e., "What happens to the density of an object when you cut it in half?" "Each half of the object is… a. …half as dense as before you cut it. b. …twice as dense as before you cut it. c. …the same density as before you cut it."). These assessments were developed, tested, and subsequently

refined in previous work (e.g., Houghton et al. 2000). Some of the density questions were adapted from Smith and colleagues (Smith et al. 1994).

Density and Pressure Interviews

Students were individually interviewed with each interview lasting approximately 30–40 min. Each interview was comprised of open-ended questions focused on a density or pressure-related phenomenon. It was conducted as a structured clinical interview with a series of questions and then a standard set of follow-up probes, such as, "Can you tell me more? I want to understand your whole idea" and "Can you explain in more detail?" Students were invited to draw diagrams or models of their ideas. These interviews were scored for density and pressure understandings and for the student's metacognitive comments, as outlined below. The final section offered scaffolded cueing of the causality involved where students were asked increasingly targeted questions about the nature of the causality involved. If they didn't spontaneously mention causality, they were asked a direct question, such as, "Does what we learned about relational causality help you to think about any of the questions here?"

Assessments of Classroom Interactions

As a means to reveal how students used the moves, we encouraged the use of white boards to model and serve as the basis for both the discussion of and reflection upon their ideas and thinking. These offered informal assessments and were videotaped for later analysis. Students drew models of their initial ideas, enabling us to consider how students used metacognitive moves on an intrapersonal level. Afterwards, they discussed their ideas with class members. The teacher prompted critical debate by asking the class questions such as the following: "What makes sense to you about Ian's model?" "What do you think is confusing about Ian's model?" "Do you believe his model?" "How would you change Ian's model to have it make sense to you?" "How does his model help you think about other ideas we've learned about?"

Daily field notes, videotapes of class discussions, and samples of students' writing provided additional informal assessments of how students used metacognitive strategies on an intrapersonal level and whether they challenged themselves to think metacognitively, whether their reflections on their own thinking changed, and so forth.

Scoring and Analysis

Scoring and Analyzing Students' Metacognitive Comments

Students' metacognitive comments were analyzed through a process of open coding. Two researchers independently evaluated students' comments, the inherent dimensions of each, and the categories that they represented. The overarching categories

Table 5.2 Categories of cognitive and metacognitive strategies

Category	Cognitive or metacognitive strategy
A	Explicit knowledge claim—cognitive statement
B	Explicit knowledge claim + reflective abstract reasoning (*intelligibility*)
C	Explicit knowledge claim + reflective abstract reasoning using "real world" models (*intelligibility* + *wide-applicability*)
D	Explicit knowledge claim + recognition and reflective exploration of the limitations of their own thinking using "real world" models (*intelligibility* + *wide-applicability* + *plausibility*)

were discussed and refined and used to independently score instances of individual and class metacognition.

Individual metacognitive comments were assessed using interview data and writing samples including their science journal entries. To examine the use of metacognitive strategies in class, we open-coded key class discussions around the causally focused activities. Focused on the underlying causal structure, these activities played a key role in exhibiting the strengths and weaknesses of students' understanding and application of causal structures. To explore how metacognition potentially helped facilitate the transfer of causal understanding, 20-min sections of discussion surrounding the same causal activity were videotaped and coded for the number of metacognitive strategies for each class.

Four categories of metacognitive and cognitive strategies emerged in students' comments (See Table 5.2). Metacognitive moves were rarely used in isolation. Students often used a combination of these moves at different levels of sophistication. Notice that these categories are additive in the sense that category B includes the criteria for category A, category C includes A and B, and category D includes A, B, and C. Each student was assigned a score for each metacognitive move and a "Total Metacognitive Score" that was the sum of their metacognitive moves across the categories.

Category A represents cognitive claims or knowledge statements that were not reflective in nature. This type of thinking was explicit in the sense that a student clearly stated what he or she thought, without an awareness of the status of why they thought what they did. It did not fit our working definition of metacognition because it did not involve students' awareness of the content of their own thinking. Nor did it involve actively monitoring the students' own cognitive processes or help students organize their thinking to manage future problems (Hennessey 1999). For example, a student's response using category A when asked, "What do you think causes a hot air balloon to rise?" was "I think that the hot air rises, forcing the hot air balloon to go up. Once it gets cold, it will start to sink (Student #153)." The student did not reflect on the status of why he thought hot air causes the balloon to go up and why the cold air made the balloon sink.

Statements where students backed up their explicit knowledge claims by negotiating the intelligibility of the idea were scored as category B. It included statements

where students considered if the idea that they stated truly makes sense to them by thinking it through on an abstract level. This is a fundamental aspect of metacognition. According to Beeth (1998a), a teacher in his study commented that by backing up knowledge claims and overt discussion on how an idea makes sense to students, the students began learning to think "both with their ideas and about their ideas." An example of a category B statement was given when a student was asked if two pieces of aluminum of different volumes have same density. The student responded, "They are both solid pieces of aluminum, but this one has a bigger volume. The other has a smaller volume. This one has a bigger mass. The other has a smaller mass. But I still think that volume for both of them would fit. It's kinda of like this … let's just say, for example that the volume is 4 cm^3 [the larger piece] and the smaller-sized one is 2 cm^3. The mass of this [smaller one] is 1 g. The mass of this [the larger] is 2 g. The mass of both of them is distributed evenly. Therefore the density must be the same (Student #73)." In this example, the student reasoned himself into understanding that the density of the two pieces of aluminum must be the same because of the outcome of his calculations based on the mathematical equation for density.

Category C combines the sense-making dimension of intelligibility with the connection-making aspect of wide-applicability. The essence of category C involves debating whether or not an idea made sense by placing the idea within a meaningful context. By connecting new ideas to familiar contexts, a student considered whether or not an idea makes sense to him or her. The following response to a question about a piece of steel wool and a solid piece of steel of the same volume was scored as category C. The question was posed, "Do you think they have the same mass?" In response, the student replied, "They used steel for a lot of buildings back before the 50s, so it would be stronger, so it would have to have a greater density to hold up all the weight. But I know that steel wool is sometimes used almost as sandpaper and so it would have to be light, because no one would want to have to carry something that is five or ten pounds across something. So I'd have to say that [solid] steel has a greater mass (Student #70)." In this example, the student made a connection to the practical application of solid steel as a construction material and the use of steel wool as a scouring pad. It was scored as category C because the student considered whether or not the two objects had the same mass by thinking about their function in the real world—using both intelligibility and wide-applicability.

The final category, category D, employed the use of all three metacognitive moves: intelligibility, plausibility, and wide-applicability. Accordingly, students used reflection to push their ideas by making connections and considering alternative explanations for an idea. Students were aware of the fact that they held two different theories to explain one idea. They may have talked their way through the idea through abstract reasoning and connection-making in attempts to determine which idea to believe. Students may also have recognized temporal differences in their thinking. That is, they may have recognized that they held different ideas at different times, perhaps before and after a particular discussion or class activity.

For example, in the pressure interview, a student explained what pressure was and whether it could change in the following response:

> In definition, pressure is just the amount of force put on an object. It's just the amount of force put on an object. Um, the mathematical equation is force divided by area, which would mean if you had 5 Newtons on say, the cassette holder. And that was say, 10 cm^2 or something. Then it would be .5 as the amount of Newtons per cm^2. Other than the definition, the way I think of pressure—I think of in and out as one pressure, instead of having it as pressure one way or the other … I think that it can change. It all depends on where you are. Like, if you are on Mount Everest, the pressure is obviously going to be extremely low…. If you're at the bottom of the ocean … you'd have the air pushing down on the water, and you'd have all the water in the ocean pushing down on it, so it would be an extreme amount of pressure. And that's why scuba divers can only go so far … right at sea level, it's like 15 lbs/in^2…. What I would say it would roughly be, the max, even for the most almost super-human person who could endure so much, I think the max could only be like 19.5. 'Cuz if it's 15 lbs./in^2, a square inch isn't that much, but the extra four lbs. multiplied by, who knows how much, it would be at least a thousand extra pounds on your body. That would mean that there would be a lot pushing out, which would make it really hard to comprehend.

In this example of a category D statement, the student began by providing different ways of thinking about defining pressure. In explaining alternative ways of explaining pressure besides the mathematical formula, the student talked about the "in and out" of pressure. In this sense, he picked up on the idea of pressure differentials as explained as a form of relational causality. By providing an additional definition of pressure besides the mathematical equation, he tested the limits of his understanding by expressing multiple lenses to view the problem (plausibility). He goes on to explain how pressure can change by applying his ideas about pressure in different contexts (wide-applicability). He also talked about pressure in higher and lower situations and the dynamics of how pressure changes between these two extremes. In this way, he tested the limits of his thinking by making connections.

Scoring and Analyzing Students' Causal Understanding in Science Concepts

The written assessments of students' understanding of science concepts were scored using rubrics developed in an earlier phase of the project. These assessed the level at which students grasped the structure of the concept on a scale from 0 to 5 and proceeding from a non-causal response to a relational causal response. These scoring rubrics are further elaborated in Grotzer (2003).

After scoring for the number of each of the cognitive and/or metacognitive categories (described above) that the student used in their writing samples and post-unit interview, a Total Metacognitive Score was arrived at by adding up the instances of individual metacognitive category use for each student. This score was compared to posttest scores and the overall gain scores on the science unit assessments and students' ability to transfer the underlying relational causal model from density to pressure. The data was further dissected to compare the scores for each individual metacognitive category to posttest scores on the unit assessments to see if some categories correlated to a higher extent than others with the science assessment outcomes.

Outcomes and Discussion

Our analysis suggests a strong correlation between the number of metacognitive comments students made during their interviews and higher science assessment posttest scores. Students who made more metacognitive statements were also more likely to offer relational causal responses on their posttests, reflecting an ability to incorporate complex causal concepts to a greater extent. They were also more likely to transfer their understandings from density to the context of the pressure unit.

Students in all classes showed significant gains on the pre- and post-assessments (t (17) = −7.56, $p < .0001$), explaining 49% of the variance in scores suggesting that the curriculum was effective in helping students learn the density and pressure concepts embedded in difficult causal concepts. This was expected based upon previous research (e.g., Basca and Grotzer 2001; Houghton et al. 2000). Students who made greater numbers of metacognitive statements also had higher density post-scores. The total number of metacognitive statements on the post-interview for density was a significant predictor of density posttest score (F (1,18) = −11.41, $p < .0001$), accounting for 34% of the variance. Entering density pretest scores and metacognitive statements on the density post-interview into a multiple regression analysis, together they explain 63% of the variance in scores. Both were significant predictors (F (1, 18) = 12.19, $p = .0033$) and (F (2, 18) = 6.03, $p = .0268$) for density pretest score and metacognitive statements on the density post-interview (Total Metacognitive Score for Density), respectively. Figure 5.1 details the parameter estimates.

Students improved significantly in their ability to detect the underlying relational causality from pre- to posttest (t (17) = −4.97, $p < .0001$), with means of .67 ($SD = .59$) and 1.55 ($SD = .70$), respectively. Metacognitive score on density was a significant predictor (F (1, 18) = 5.03, $p = .04$) of students' ability to detect relational causal models on their posttest, explaining 24% of the variance (Density Relational Model Score = 0.49 + 0.11 × Total Metacognitive Density Score). Interestingly, pretest scores were not a significant predictor of posttest scores (F (1, 18) = 1.92, $p = .18$), explaining little of the variance ($R^2 = .10$).

Next, whether metacognition played a role in the transfer of learning gains in density to pressure was examined. Transfer was defined as detecting at least one relational model on a density posttest to reveal that they learned the base concept and then showing understanding of at least two of the possible three relational models on the pressure posttest to show that transfer to the target. A regression analysis revealed density posttest score to be a significant predictor of pressure posttest scores

$$\text{Intercept} = -0.67 + \left\{ + 1.07 \times \text{Density Pretest Score} \right\} \left\{ + 1.24 \times \text{Metacognitive Score on Density} \right.$$

Fig. 5.1 Prediction formula detailing parameter estimates (density pretest scores and metacognitive scores) to estimate density posttest scores

(F (1, 17) = 6.10, p = .03), explaining 29% of the variance. Of the 18 students in the subset, all but two had at least one relational model on the density posttest. Of these, only one student did not show a relational model on the pressure posttest. Metacognitive performance on the density post-interview was a significant predictor of whether or not students transferred the models as defined above (F (1, 15) = 4.73, p = .05), explaining 27% of the variance (Transfer Score = 0.23 + 0.06 × Total Metacognitive Density Score).

Students employed a diverse range of metacognitive strategies. In interviews, the most frequently used strategy was category B, explicit knowledge claim plus abstract reasoning to think through a particular idea. Higher scores of category B correlated to overall posttest scores (r = .25, p = .03). Yet, during classroom discussions, category D, exploring the limits of students' ideas using all three levels of metacognition (intelligibility, plausibility, and wide-applicability), surfaced the most frequently in both classrooms. Of the total metacognitive strategies used in both classes, category D was used 42.0% of the time, while category B was used 28.4% of the time, and category C was used 29.6% of the time.

The following category D statement shows a typical pattern in students' thinking, that is, the recognition of changes over time in his or her thinking. For example, when asked, "What's going on when density changes?" a student replied, "Well, I thought at first that it was kind of like a chemical change. It can be changed chemically, I think, but a physical change can also be done like compacting bread or pouring something in [to make it a mixed density] (Subject #112)." After doing the experiment, the student noticed how her thinking changed, and she was able to recognize the emergence of her new understanding.

At the end of the pressure interviews, students were asked to note any metacognitive strategies that were particularly useful to them. Students' responses indicated that comparing their ideas with other students' ideas and making connections to other areas of their learning were the most useful. The results of this self-assessment were consistent with the outcome of the interviews. Students with higher scores on these two strategies (intelligibility + wide-applicability) had higher overall gain scores (r = .27, p = .03). This supports the notion that students learn effectively by comparing their ideas to other students' ideas. It also supports the claim that connecting new ideas to familiar contexts helps students understand learning objectives. For example, at the end of a pressure interview, a student said:

> I remember how we were doing the balloon over the flask we did it in two different ways, getting the balloon in and getting the balloon out and that helped because you have to reverse your thinking and think about it in different ways. The more experiments you do, it's easier to connect things like concepts. And it's easier to believe it, once you see it. I think I'm more of a visual learner. If I see it, I can believe it more and comprehend it better. And I guess that helped a lot because a lot of times in science you can't explain a lot of things because they're just too hard. And you can't, like, visually show them. It's easier when you have an experiment and you have to reflect on it too. Like, what you understand about it and what you don't 'cuz it helps you to get a better understanding and learn more. And the practical application, like how we had to answer those questions about…, like, why are runways longer in Denver and San Francisco? It made you practically think about it. So it's not just like some topic you learn in school because you can like really apply it to the

> world. And, like, the airplanes, I never really realized how the difference in pressure above the wing and below the wing gave it like the plane lift. I never really thought of it that way. But now I can apply it and realize that's how the plane works and it makes more sense too because it's connected to something.

She reveals a sophisticated understanding of what's useful to her in her own learning and the importance of connection-making.

Which, if any, of these metacognitive strategies appeared to help students transfer their causal understanding between topics? There were many examples where students who made more metacognitive statements in the course of their interviews were also more likely to map the relevant analogical relationships when transferring concepts. In each case, they needed to detect the relationship of balance or imbalance between two things and figure out how to map it appropriately. This mapping did not always happen quickly and easily. Often students talked through how two concepts, for instance, how liquid gets pushed up a straw and why balloons get pushed out of car windows, mapped on to each other, considering and rejecting mappings that did not work along the way. Often multiple metacognitive strategies were utilized simultaneously, making connections as evidence to make sense of an idea, rather than purely abstract connection-making. For example, when thinking about what happens when drinking from a straw, one student compared independent and dependent clauses in English and their interdependence to how a straw works and how the two pressures (higher and lower) need to work together for an effect. The student actively reflected on what she had already learned about relational causality in a previous unit. She uses the third metacognitive tool "wide-applicability" to think about relational causality in a context that makes sense to her.

While individual metacognitive scores showed a clear relationship to greater transfer, interestingly, class metacognitive scores did not predict whether students transferred the models or not (F (1, 15) = .38, p = .54), explaining almost none of the variance in scores. However, there were clear instances where students appeared to influence one another and a culture of metacognition clearly emerged. The following exchange ensued in a classroom where the teacher explicitly facilitated a conversation about how relational causality helped students in revising their models of how a straw worked before and after an experiment designed to help them.

> Student 1: I might have subconsciously made the connection. I knew what was happening—like, I knew one thing would affect the other, but I didn't go the extra step to put two and two together to get that it's relational causality…. I would say it [relational causality] did really help because I understood what was going on and how one could change the other. By throwing in relational causality it would kind of change what I was thinking about originally. Like, I guess I thought it was more or less a "Domino thing," that one thing would make the next happen in a chain, like that. But if you think about it as a relational causality, then you would have to change your idea from one thing causing the next to happen, then they keep on causing the next thing to

happen … to that both go together to make one thing happen. Like, as you lessen the air pressure in the straw, the greater air pressure outside can force down, that makes the liquid able to rise up the straw. One thing starts the next.

Teacher: So can you say how you're thinking about it now?

Student 1: Well, like if both affect each other, then it's because that the air pressure in the straw lessening and the air pressure outside staying the same, the lesser air pressure inside and the greater air pressure outside causes the liquid to go up the straw.

Student 2: I don't think it's really like domino causality because we saw the two causes are high air pressure outside and no air pressure inside, but we already saw that with Mary's straw, there wasn't any air pressure. And she took out the air pressure from the inside the air pressure, but it didn't cause it to go up right away. It needs the other….

Student 3: Originally, I knew pressure was involved, but I never really thought of it as a relationship between high and low pressure. And to get the pressure itself is another relationship between force and area. And you can break it down and see how it works.

This conversation of this class illustrates a culture of reflective thinking. In this example, the students used all three metacognitive moves—intelligibility, wide-applicability, and plausibility. All three students interviewed from this class, despite different achievement levels, had two relational models on the density posttests (out of two possible relational questions). All three interviewees also had at least two relational models on the pressure posttest (out of three possible relational questions). Thus, all three interviewed students from this particular class met the criteria of how we defined transfer for this study. Anderson and Nashon (2006) found that the metacognitive dimensions or profile of metacognitive moves that individuals within groups employ may impact the learning of the group. A study that looks at these individual patterns and how they impact learning might address the lack of relationship between class metacognitive scores and transfer found here.

Summary

The results underscore the importance of metacognition in helping students to evaluate how they are structuring their ideas and to adopt more complex explanatory structures. Students who reflected upon and evaluated the structure of their models were more likely to realize the need to structure the concepts differently. In the classroom discussions, a clear shift in students from viewing learning as a

process of transmission and the passive role that they assume in that context to viewing learning as a process of active construction where they need to own the sense-making process took place (Gunstone 1991). The early videotapes reveal that at the outset of the study, student dropped their books on the desks and prepared to listen and take notes. Many appeared surprised when they were asked to consider the intelligibility and plausibility of the ideas being presented and initially hung back and waited. In the coming weeks, they increasingly engaged in the metacognitive moves and became much more active participants in their learning.

Students who considered the plausibility of their ideas through the negotiation of whether or not their own notions of causality made sense to them were able to gain a deeper understanding of the particular causal form. This in turn supported their ability to apply the structure flexibly to new concepts. While the findings are correlational, students who engaged in metacognitive activities were more likely to transfer their understanding of causal structures between topics than those students who were not engaged in metacognitive activities. Students' preference for category C, intelligibility and wide-applicability, underscores the importance of connecting new ideas to familiar contexts and to helping students learn by comparing their ideas to other students' models. This type of comparison is a part of many modeling approaches where students try out various models and evaluate them in comparison to other models and which most effectively explains the evidence.

The above exploration underscores the promise of metacognition when there is deep structural knowledge to be learned and transferred (Zohar 1994). By encouraging deeper processing and giving students ownership for their sense-making, students are more likely to understand the logical structures, causal relationships, and mechanisms involved in the particular science content (Chin and Brown 2000; Zohar 1994). Given students' tendency toward default patterns, metacognition invites students to realize, reflect upon, and perhaps ultimately revise the underlying causal structures that they assign to particular concepts. This ultimately should enable them to develop a broader repertoire of causal concepts and also a reflective awareness about where they may apply. In turn, this should encourage deeper understanding in science and a greater likelihood that students will be able to deal with complexity in their lives.

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Appendix 1: Example of Materials-Based Metacognitive Activity in Density

Reflecting on What You've Learned About Changes in Density

In the past few classes, we have considered what causes differences in density at the microscopic level and how density can change. In your journal, please answer the following questions:

1. Of what you've learned about what causes differences in density, what makes sense to you? Are there any pieces of what you've learned that seem especially clear to you? What about it makes it easy to understand?
2. Of what you've learned about what causes differences in density, what doesn't make sense to you? What pieces seem especially difficult to understand? What about them makes them difficult?
3. Sometimes even when we understand an idea, we may not believe it. Comprehending an idea is not the same thing as believing it to be true. In terms of density, is there anything that you believe to be true? Why do you believe it to be true?
4. Is there anything that you believe is not true? Why do you believe it is not true?
5. Is there anything about what you learned about density that relates to other ideas you may have learned about? What are they? In what ways do they relate?

Appendix 2: Example of Teacher-Supported Metacognitive Activity in Density

Reflecting on Our Thinking as a Group

The more we can begin to understand our own thinking, the better we understand and process ideas in science. As an exercise to help us reflect on our thinking as individuals and as a group, we will watch a video from yesterday's lesson. As you watch the video, look for ways in which you use each other to make sense of ideas, to consider the plausibility of ideas, and to connect ideas to other areas of learning. Here is a list of possible situations to look for:

Instances where…

- When talking about his or her model, a student explains what makes sense to him/her. The student may explain why certain pieces are particularly clear and easy for him/her to understand. He or she may also talk about things that still seem unclear about an idea.
- After one student shares his/her response, other students understand the original student's model, they may understand parts of the model, or they may not understand the model at all.

- Students discuss their different understandings. After one student shares his or her model, other students in the class add to the first student's model to have the idea make sense to them.
- Students talk about whether or not they believe a particular model. Sometimes even if a model makes sense, you may not necessarily believe it. Can you recognize any examples when a student (or a group of students) talks about "getting" a particular model but not necessarily "buying" it? In other words, instances when students debate whether or not an idea is true?
- In the discussions, were there any instances when students referred to common experiences that you, as a class, have shared (or maybe not shared) that made thinking about this idea difficult to understand?
- Were there any common experiences or understandings that the class shares that helped class members make connections about this idea to other areas of learning? Was there any common theme that students tended to refer to when explaining their ideas?

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Chapter 6
Self-regulated Learning and Conceptual Development in Young Children: The Development of Biological Understanding

David Whitebread and Valeska Grau Cárdenas

Introduction

The type of learning needed in our society, where an immense amount of knowledge is available, has to do not only with the acquisition of structured knowledge but also with the mastery of learning skills and tools involved in the lifelong learning required in the 'information society' (Delors 1996; OECD 2008).

The relationship between learning knowledge in specific domains and developing independent learning skills is an important issue when planning educational curricula. However, there is little consistent research literature about how knowledge and skills develop in young children within classroom contexts. From the field of psychology of learning, the concept of self-regulated learning (SRL) is an important theoretical development which relates to independent learning skills and the way in which these abilities help students to learn and succeed in educational contexts. SRL has different definitions, but it is generally assumed to be 'an active, constructive process whereby learners set goals for their learning and then attempt to monitor, regulate, and control their cognition, motivation and behaviour, guided and constrained by their goals and the contextual features of the environment' (Pintrich 2000, p. 453).

Considering also the growing evidence that human cognition is not only domain-general but also domain-specific, which means that many cognitive abilities are specialised in relation to certain types of information (Hirschfeld and Gelman 1994),

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it is necessary to adapt models of self-regulated learning to particular disciplines or domains of knowledge. In the research reported in this chapter, the domain considered is biological science, which is recognised, alongside physics and psychology, as one of the three core domains in human cognition (Hatano and Inagaki 1996; Keil 1992; Wellman and Gelman 1992). As such, it involves children's possession of 'naïve' theories explaining biological phenomena, raising common difficulties for conceptual learning and interesting educational challenges.

Hence, this chapter aims to bridge the research traditions of self-regulated learning and conceptual learning within a domain, which up to this point have developed separately (Sternberg and Grigorenko 2003). We begin the chapter by reviewing existing literature in this area and attempt to present and bring together different theoretical and methodological perspectives on the study of self-regulation of learning and conceptual development in science, and to contribute to our understandings of how these processes come together and interact during the first years of schooling.

The study presented at the end of the chapter was intended to explore these theoretical relationships. Adopting a social constructivist approach to the study of the phenomena, and a multiple case study as a methodological strategy, eight children from third grade of primary school were followed during one academic semester within different contexts of academic activity. The objective was to gather information regarding how they regulated their activity while solving specific tasks or interacting with their peers and, at the same time, collecting evidence regarding their development of scientific concepts reviewed in the classroom.

Learning to Learn: An Integrative Model of Self-regulated Learning

Self-regulated Learning and Metacognition: Clarifying the Concepts

As a starting point, we would like to discuss why we are using the concept of SRL and in which ways this concept is related to metacognition. SRL is far from being considered a unitary concept, and researchers have struggled to resolve basic issues such as the conceptualisation and the operationalisation of self-regulatory capacity, concluding that there is no straightforward definition of this theoretical construct (Boekaerts and Corno 2005; Butler 2002; Puustinen and Pulkkinen 2001). As Boekaerts and Corno (2005) highlight, self-regulation includes a complex combination of several psychological concepts in the field of cognition, problem solving, conceptual change, metacognition, motivation and volition, each of them with its own research traditions, which add more complexity to the study and definition of the phenomenon. Therefore, there is a lack of clarity regarding how all these motivational, affective, cognitive and metacognitive processes interact to generate self-regulation (Efklides 2005).

Nevertheless, there are several commonalities among the different approaches to the study of SRL. All the models assume that students are self-regulated learners if they are able to engage actively and constructively in their learning processes, and are usually described as metacognitive, intrinsically motivated and strategic (Winne and Perry 2000; Zimmerman 1990). Metacognition, in this context, has to do with the awareness or knowledge of cognitive strengths and weaknesses and strategies needed in order to meet the demands of challenging tasks. Intrinsic motivation is related to the belief that ability is incremental (i.e. that abilities are changeable and can be improved by effort) (Dweck 1999) to high self-efficacy for learning (i.e. a belief in one's own capabilities) (Bandura 1997) and to a focus on progress and deep understanding (i.e. a 'mastery' rather than a 'performance' orientation) (Dweck and Legget 1988; Elliot 1999; Pintrich 2000). Being strategic is reflected in the choice of the most suitable strategy to solve a problem and the appropriate application of it (Perry et al. 2004). Likewise, self-regulated learners are able to use certain standard criteria to direct their learning and set their own goals. Finally, there is agreement regarding the conception of self-regulatory activities as mediators between personal and contextual characteristics and actual performance, i.e. that an individual will adopt different self-regulatory strategies depending upon the relation between the characteristics of particular tasks and their personal goals and abilities (Boekaerts and Corno 2005; Pintrich and Zusho 2002).

Based on this characterisation, it is not difficult to appreciate that this theoretical construct could be very useful when school learning contexts are considered. Self-regulated learning is related to the capacity for 'learning to learn' and independent learning skills, both important issues addressed by the educators and governmental policies of different countries as a relevant tool within school and lifelong learning (Delors 1996; Whitebread et al. 2005).

Although it is possible to infer some relationships between metacognition and SRL throughout the paragraphs above, we would like to state our assumptions and understanding more clearly, since this relation is still an unresolved issue in the literature (Veenman et al. 2006). Regulation has been often used as an umbrella term, including metacognitive monitoring and control. Nevertheless, current trends in the field conceptualise metacognition as referring specifically to the monitoring and control of cognition, and self-regulation as referring to the monitoring and control of a broader range of human functioning, such as cognitive, social, motivational and emotional aspects (Whitebread and Pino Pasternak 2010). According to this view, we see self-regulation as a broader concept than metacognition, and precisely because of the inclusion of more affective and social aspects, it seems more applicable to the study of learning in classrooms contexts.

The Theoretical SRL Framework Used in the Present Study

The research presented in this chapter aimed to investigate the phenomena of SRL in children (8–9 years old) performing academic activities in natural contexts. This objective presents a challenge in terms of the research design and the creation of

ways to evaluate children's self-regulated learning abilities while engaged in activities, as the measures of self-report – most commonly used to research SRL with older students – would not be sufficient to gather the necessary information for children of this age group. This is aligned with Winne's (2010) claim regarding the contextual nature of SRL and the constant dynamics between contexts and individuals.

In the absence of consensus regarding theoretical models of SRL, we constructed a general framework which guided the data collection and analysis in the present study. Within this framework, self-regulated learning is conceptualised as being present at three main levels of understanding of the phenomena, following Rogoff's (1997) conceptualisation of three planes of analysis of development in context: personal, interpersonal and the community. The personal plane makes reference to how a person changes and interprets the situation when participating in an activity. The interpersonal plane is a view of the processes occurring between people, with tasks and with tools, shedding light on the reasons behind people's choices, selection of strategies or influence on each other. Finally, the community plane describes the social, historical and cultural setting.

The inclusion of these three levels of analysis of self-regulated learning behaviours in the classroom context helps to illustrate our understanding on how SRL is observed and interpreted in the present research: the focus is on individual cases, represented by the personal level of regulation and therefore including metacognitive knowledge and regulation processes; however, this personal understanding is continuously influenced by interpersonal and socio-cultural constraints, which contextualise the individual findings. In fact, the interpersonal level of regulation is represented through analysis of the cases interacting in a group, which contributes also to the understanding of more social aspects of SRL.

In the following paragraphs, the most important aspects included in this understanding are described in the context of the present research, starting with the individual level: metacognitive knowledge and regulation processes. Following this review, an account is provided of the concepts appearing at the interpersonal level, such as the development of group cognition and shared regulation of learning.

The Personal Level: Metacognitive Knowledge and Regulation Processes

Metacognitive Knowledge

The term metacognitive knowledge was originally introduced by Flavell (1987) who defined it as knowledge of cognition about one's own or someone else's cognitions, motivation or emotions. Therefore, it refers to the knowledge a person has acquired that has to do with psychological issues.

Flavell (1987) subdivided metacognitive knowledge into three categories: knowledge of person variables, knowledge of task variables and knowledge of strategy variables. Knowledge of person variables is related to the acquired knowledge regarding personal or other's cognitive, affective or motivational characteristics. Knowledge of task variables makes references to individuals' learning of the demands

of particular tasks. Finally, knowledge of strategy variables refers to knowledge of procedures or cognitive strategies needed to achieve particular learning goals. Pintrich (2000) also includes in his definition of SRL the regulation of contextual factors, referring to knowledge of the context in which the activity is taking place, such as availability of resources, classroom environment, teacher characteristics, etc.

In the research presented in this chapter, metacognitive knowledge was not frequently observed by itself within the data collected, as the predominant type of behaviour observed was on-line regulation of learning or regulation and control processes. Metacognitive knowledge was rather observed as embedded in these processes of regulation, which are outlined in the next section.

Regulation Processes

Essential in every model of SRL are, of course, explanations regarding how individuals regulate their own learning processes. Traditionally, within the literature concerned with pure metacognition, regulation processes have been researched only as regulation of cognitive processes; however, other areas of regulation have been incorporated from more socio-cognitive perspectives into models of SRL. These include motivation and affect, behaviour and context (Dweck and Master 2008; McInerney 2008; Pintrich 2000; Zimmerman and Schunk 2008).

In general, different sub-processes of regulation are described, which refer to different phases of the process. Many models of metacognition and SRL agree upon the four main phases of regulation, namely planning, monitoring, control and reflection (Pintrich 2000; Zimmerman 2001). Following the definitions provided by Pintrich (2000), planning involves activities performed by individuals before they engage in an activity, including for example goal setting, activation of metacognitive knowledge and perception of different aspects related to feelings of efficacy, interest, task value and perceptions of the task and the context. Monitoring refers to ongoing processes related to awareness of different aspects of the self, the task or the context, including feelings of knowing, judgments of learning, awareness of motivation and affect and the performance of the task in relation to the context. Control and regulation processes would appear as a result of the ongoing monitoring and represent efforts to regulate different areas of the self, the task or the environment, including selection and adaptation of cognitive strategies, management of motivation and affect or adequacy of effort in relation to contextual constraints. Finally, reflection relates to evaluations of the self, task and context, such as cognitive judgments and attributions of performance.

Pintrich (2000) explicitly stresses the fact that the phases are suggested as a way to organise our thinking regarding SRL but not to imply that all academic learning follows these phases. Furthermore, they could be ongoing almost simultaneously as the student progresses through the task, without being clearly observable as separate processes.

It is important to mention that although these concepts related to regulation processes have been defined from early models of metacognition and SRL, the research on the integration of cognitive, motivational, affective and contextual

factors has been a rather recent phenomenon, as before the main emphasis was on the description of merely cognitive aspects of SRL. In the light of these new understanding of SRL, the data collection and analysis included motivational regulatory elements.

The Interpersonal Level: Social Aspects of Regulation of Learning

Although self-regulated learning has been defined and researched mostly as an individual process, from the area of problem solving in small groups, some authors have suggested that metacognition and regulatory processes could have an interpersonal level (Goos et al. 2002; Iiskala et al. 2004; Vauras et al. 2003).

It has been observed that during episodes of true collaboration, cognitive regulation processes fluctuate among three levels: self, other and shared regulation. Self-regulation refers to the traditional concept regarding the monitoring and control of individual performance, or intra-personal regulation. Other-regulation relates to the situation in which one partner masters a key element of the task but the other(s) does not. As a consequence, that partner instructs the other(s). Finally, shared regulation defines an 'egalitarian, complementary monitoring and regulation over the task' (Iiskala et al. 2004, p. 150). Hadwin and Oshige (2011) call this phenomenon 'socially shared regulation' describing it as the processes by which several others regulate the collective activity. In this sense, the regulation is collective and the regulatory processes and products are shared.

There are still very few research studies in this area, but they are usually characterised by having the collective interaction, more than the individual, as the unit of analysis.

In this framework, the interpersonal level of regulation called 'shared metacognition' or 'shared regulation' (Iiskala et al. 2004; Vauras et al. 2003) exhibits characteristics that distinguish it from intra-personal metacognition with regard to the cognitive activity involved: working through collaboration could allow the students to reduce the cognitive processing load, but at the same time they need to monitor and regulate the reciprocal use of the joint representation of the task (Iiskala et al. 2004). King (1998) also suggests that when peers develop high-quality collaboration, there is such interdependence between the participants that the thinking processes seem to lie in the transactions.

There are still not many studies looking at this phenomenon, and the development of methodologies is still in an incipient state. Iiskala et al. (2004), using a modified version of the 'interaction flowchart' designed by Sfard and Kieran (2001), demonstrated that metacognitive activity appeared very frequently during the course of the student's joint construction processes, especially when the mathematical problems they had to solve were particularly challenging. Whitebread et al. (2007), using observational coding of categories within a study with preschool children, demonstrated that children showed more evidence of metacognitive monitoring and regulation when they were working by themselves in small groups, as opposed to working individually or with the guidance of an adult.

Having reviewed the main concepts related to our understanding of self-regulated learning, we will proceed to reviewing the conceptual change literature that has also been implicated in the design of the present research study.

Learning Science in School: Contributions from the Conceptual Change Perspective

Conceptual Change in Science

When learning processes in specific school domains are addressed, and particularly in science education, the conceptual change literature has made important contributions. Starting from a rather cognitivist standpoint in the 1970s and 1980s, and moving to the integration of more affective socio-cultural aspects in the 1990s (Sinatra and Mason 2008), the conceptual change literature has addressed the problem regarding how people learn by formulating domain-general theories through general models of knowledge acquisition, as well as conducting domain-specific empirical research to explain learning in particular disciplines (Murphy and Alexander 2008). Probably the most interesting contribution so far is the clear demonstration – through a considerable body of research – that learning about the natural world requires overcoming certain conceptual obstacles, represented by children's pre-existent knowledge and 'naïve' theories which conflict with the information, ideas and scientific models provided in the classroom (Sinatra and Mason 2008).

Conceptual change has been defined as 'a process through which students' initial understanding or beliefs are altered to more closely align with scientifically-held understanding' (Murphy and Alexander 2008, p. 605).

Addressing the mechanisms of conceptual change, the classical approaches tended to affirm that the change from one theory framework to another was abrupt and occurred within a short period of time. However, Vosniadou et al. (2008) claim that – without denying the possibility of such a sudden change – conceptual change appears to be a rather slow process and that, even when the so-called 'radical' conceptual change is reached, it is often the product of a gradual process rather than a sudden insight experience. In this way, these authors claim that students use an enrichment mechanism that could be to a great extent unconscious, and the resulting small additions might produce conceptual change at some point, given certain conditions. They also argue that these enrichment mechanisms are responsible for the creation of 'misconceptions' or 'synthetic models' because they constitute an attempt to combine two pieces of information that are incompatible: one from the student's original, or 'naïve', theory and another from the scientific theory they are trying to learn. Another explanation of the origin of a misconception is the location of new information added into an inappropriate schema (Chi 2008). These are all ways in which the contradictions between students' naïve experiences and formal science concepts present particular difficulties in relation to conceptual change in science.

Inagaki and Hatano (2002) classify these changes into two types of conceptual change. One of them is named 'spontaneous conceptual change' which is a result of children's increasing experience with their environment, which includes school instruction; this type of change can be achieved without conscious effort or systematic instruction. The second type is the 'instruction-based conceptual change', accomplished through systematic teaching, involving effort and awareness from the learner. This is a stronger version of conceptual change and is needed for the learning of some complex conceptual devices, such as photosynthesis or evolution theory, which are both concepts that cannot be inferred without instruction.

Intentional Conceptual Change

Paralleling trends in the metacognition literature, there has also been a 'warming trend' in the literature of conceptual change (Sinatra 2005) involving the inclusion of motivation, affect and context in the research on this phenomenon. Most of this literature is located under the umbrella of what is called 'intentional conceptual change' (Sinatra and Pintrich 2003), defined as 'goal directed and conscious initiation and regulation of cognitive, metacognitive, and motivational processes to bring about a change in knowledge' (p. 6).

Looking at the general definition of intentional conceptual change (ICC), the commonalities with the literature of self-regulated learning are evident. There is an emerging framework claiming that learners are not only active in constructing meaning, but they can be *intentional*. The notion of intentionality includes concepts such as cognitive goals, conscious control, and purposive use of knowledge. Thus, intentional learning can be defined as 'the deliberate and purposive learning initiated by intrinsically motivated learners under their full conscious control' (Vosniadou 2003, p. 379). This makes it clear that there are some constructs related to intentionality which are also present in the research related to metacognition, self-regulated learning and conceptual change (Hennessey 2003).

Sinatra and Pintrich (2003) describe the main features of intentional cognition as internal initiation of thought, goal-directed action and conscious control. They argue that intentional learners not only cognitively engage in the learning process but also monitor and regulate their learning in a metacognitive way, being influenced by the motives, goals, beliefs and emotions they bring to the learning process.

Vosniadou (2003) argues that intentional learning may facilitate the effective development of conceptual change through different processes: monitoring learning, providing metaconceptual awareness (i.e. understandings of different 'naïve' and scientific beliefs and assumptions), affording abilities to entertain multiple representations (i.e. different ways of looking at a problem or phenomenon), providing the opportunity to acquire more sophisticated epistemologies in science (i.e. understandings about the nature of scientific knowledge, evidence and theory) and facilitating more efficient mechanisms of conceptual change.

Thus, the concept of ICC involves a bringing together of some aspects of self-regulated learning and knowledge acquisition through conceptual change. Limón (2003) has defined an interesting model of the relationship between ICC and domain-specific knowledge (DSK). She argues that three prerequisites are necessary for ICC: first of all, there is a *metacognitive* prerequisite, which requires individuals to be aware of the need for change and to be able to know what needs to be changed. The individual has to recognise the available resources, such as prior knowledge, motivation and epistemological beliefs, which may impede or facilitate the awareness of the need to change. Secondly, there is a *volitional* prerequisite, implying that individuals must want to change, considering change as a personal goal and not one imposed by others.

Finally, there is a *self-regulation* prerequisite, meaning that individuals must be able to self-regulate their process of change, planning, monitoring and evaluating them. Limón (2003) affirms that individuals who are able to self-regulate their change process should be aware of their knowledge and beliefs; they should be willing to change, identify what needs to be changed and maintain engagement in the task. They also should be able to plan, monitor and evaluate their motivation, emotion, interest, strategic skills for achieving the goal of change, and to plan and monitor activities that can help the process of change and evaluate the results of this process. Moreover, they have self-management skills that help them to handle stress, anxiety and boredom, which facilitate willingness to change.

This model of intentional conceptual change has several possible consequences in the application of strategies for teaching and learning processes. Limón (2003) suggests that the learning goals and their implications for self-regulation of motivation, knowledge and beliefs should be explicitly communicated to learners and taught and evaluated in schools. Likewise, social interaction may help students in the development of ICC. Teachers and parents could contribute by supporting children to develop self-regulated learning processes in class or at home. Peers are another interesting resource because it seems that work in teams and discussion among peers promote the development of ICC (Limón 2003).

Considering these issues, we would argue that it is valuable to explore the relationship between self-regulated learning and domain knowledge in the early years of schooling, in an attempt to find empirical evidence to support these theoretical developments and looking at cognitive change immersed in the natural contexts of schooling (Cole 1996). As the target domain within the present study was biological understanding, including classification of living things, photosynthesis and interactions between living things and their environment, we address this specific area of research in the following section.

Learning Biological Concepts

Biology has been considered as one of the main domains in which children posses naïve theories together with physics and psychology. These theories could be very

adaptive in children's early years; however, they can create difficulties when learning scientific explanations of phenomena (Wellman and Gelman 1992). In this section, we review the main issues regarding teaching and learning of the particular phenomena included in the study reported in this chapter.

Classification of Living Things

Within the biology domain, the main concept researched is the distinction between living and non-living things (Siegal and Peterson 1999; Springer 1999; Venville 2004). However, regarding the specific area of classification of animals and plants, there is a limited research literature. Ryman (1974) conducted a study with 12-year-old children in which he asked them to classify drawings of living organisms in pre-defined biological categories (i.e. vertebrates, invertebrates, fish, amphibians, reptiles, etc.). He reported that their understanding of classification was fairly poor, as they did not seem to possess reliable class concepts that allowed them to recognise which animals and plants belonged or not to a category.

More recently, Panofsky et al. (1990) carried out an ethnographic classroom study. Children were given a set of animals and plants, and they had to group them according to things they considered 'belonged together', and they repeated the activity three times, with some weeks in between, after a period of instruction. Children improved the percentage of taxonomical categories used in classification, but many kept using, at least partly, non-taxonomic criteria such as similarities based on perceptual similarities. Another interesting finding from this research is that many children fluctuated in the quality of categories they used, for example, starting with more taxonomical and then using perceptual similarities. In this sense, many children showed classification behaviour that showed their attempt – and struggle – in using their new learned concepts.

The authors suggest that the development from everyday concepts to scientific categories may require longer immersion than expected. They also recommend the use of teaching strategies such as active problem solving, peer interaction, teaching connected with varied media and experiences (i.e. field trips) or making classifications systems an object of study.

Photosynthesis

Photosynthesis is considered a central concept in biology because it is a key concept underpinning the understanding of more global issues such as food supplies, energy flow and ecological principles. However, the understanding of this process has been widely described as a concept difficult to grasp because it is not easily compatible with everyday notions (Inagaki and Hatano 2002; Mikkilä-Erdmann 2001; Stavy et al. 1987). Therefore, initial conceptions have to undergo a restructuring of knowledge described as instruction-based conceptual change (Inagaki and Hatano 2002).

Research about this concept has suggested that even though children do not have prior knowledge of photosynthesis, they possess views about plant activities and materials, relationships between plants and animals, functions of leaves and plant growth (Barker 1985, cited in Barker and Carr 1989).

One of the few studies carried out with young children analysed the initial framework and conceptual understanding of photosynthesis in first graders and the synthetic models they created (Vosniadou et al. 2008). It was found that most children considered plant development as being similar to animals, for example, they thought that plants took their food – water or nutrients – from the ground through their roots (Barker and Carr 1989) and this food is accumulated in small pieces. After instruction, different synthetic models were found, such as the conception of photosynthesis as a breathing process through which plants clean the air. In this case, photosynthesis has nothing to do with feeding processes. Another example of these models is the conception of photosynthesis as a feeding process through which plants take food from the ground, from the water, from the air and the light (see also Lumpe and Staver 1995; Mikkilä-Erdmann 2001; Stavy et al. 1987, describing similar alternative conceptions). Other misconceptions described are, for example, the idea that plants respire only during the night, when they are not involved in the photosynthesis process (Marmaroti and Galanopoulou 2006).

The increased use of group learning strategies has been suggested in order to overcome these problems in understanding, providing the necessary scaffolding to encourage high levels of cognitive interaction (Lumpe and Staver 1995; Ross et al. 2005). Other suggested methodologies have been the use of visual approaches such as drawing models, making models with different materials, using role playing with students being parts of the plant (Ross et al. 2005) and the design of texts that challenge student's conceptions (Mikkilä-Erdmann 2001).

Interactions Between Living Things and the Environment

Interactions of living things and the environment represent a very wide area of knowledge as it includes adaptations of animals to their environment, interdependency of organisms, gas exchange, food webs and all the concepts related to ecology. In the case of this research study, only some concepts concerned with relationships between plants and animals and interdependency between animals were covered by the curriculum which the children were learning.

Research conducted in the UK has shown that young children tend to use anthropomorphic reasoning to explain reasons for animals' interactions with other living things, attributing human reasoning and intentionality to animals. However, this is not very frequent after the age of nine (Leach et al. 1996). Another characteristic of this young age group is that, between the age of 5 and 11, children talk about individuals in the singular and not about populations. Therefore, the relationships between animals are conceived more as a one to one affiliation than interdependency between species. Also, students between five and seven have been found

to not show evidence of understanding groups of interdependent organisms in ecosystems and find difficulties in inferring the consequences of eliminating top predators from the food web (Schollum 1983).

Lin and Hu (2003) argue that the complex nature of the biological domain demands, in order to be understood, emphasis on the interrelationships among different aspects of the living world, which, in turn, adds more complexity to the required teaching strategies.

Self-regulated Learning and Conceptual Development: Case Studies in the Biological Science Class

Design of the Present Study

The study reported in this chapter had the main objective of exploring the relationship between self-regulated learning and conceptual development of biological concepts in the early years of schooling. There are several studies looking at the relationship between metacognitive aspects of teaching and learning science: for example, see the CASE (Cognitive Acceleration through Science Education) study (Adey and Shayer 1994), the META (Metacognitive Enhancing Teaching Activities) project (Hennessey 2003) and the work on Situated Metacognition (Georghiades 2004). However, studies focusing on learning in biology are rare.

Within the present study, evidence of self-regulated learning skills and conceptual development was collected in authentic classrooms following a microgenetic approach, which involves the understanding of the 'how' of the processes of development more than its products. This involves studying change while it is occurring (Lavelli et al. 2006; Siegler 1995).

The choice of a naturalistic study was based on the claim of several researchers about the necessity to collect data across contexts and at different points in time in order to capture the sophisticated nature of self-regulation processes (Hadwin et al. 2004; Perry et al. 2002; Winne and Perry 2000) and give account of how self-regulatory skills are displayed in real time and real contexts (Perry et al. 2004); for example, how students adapt strategies in different learning situations. Hadwin et al. (2004) and Winne (2010) argue that this type of knowledge about how SRL skills are deployed in real situations and the relationship between the on-line decisions students take when applying strategies and their reflection and self-perceptions has not been sufficiently explored.

Aligned with these objectives, a multiple case study was designed, including eight cases belonging to two third-grade classrooms from the same school in Santiago de Chile. Thus, four cases per classroom were systematically observed in different school situations regarding the teaching and learning of scientific concepts in order to obtain thick data of each case. The research was carried out over a period of 5 months (one academic semester) and included three phases: the preparation of

Table 6.1 Temporal relationships between teaching and evaluations

Phase	Month	Teaching	Individual evaluation	Group-work activities
Phase 1 Preparation of the intervention	March	Growing plants		Collaborative training
Phase 2 Teaching and assessment of science concepts and SRL	April	Growing plants/ Photosynthesis	Classification of living things Photosynthesis Interactions between living things and environment	Activity 1: Growing plants Activity 2: Growing plants
	May	Classification of living things	Classification of living things Photosynthesis	Activity 3: Photosynthesis
	June	Interactions between living things and environment	Classification of living things	Activity 4: Classification Activity 5: Interaction between living things and environment
Phase 3 Final assessment	July		Classification of living things Photosynthesis Interactions between living things and environment	

the intervention, the intervention regarding teaching and assessment of science concepts and self-regulated learning and the final assessment (see Table 6.1).[1]

In the first phase, several meetings were held with the teachers in order to inform and discuss the purposes of the research. In this context, they were encouraged to carry out, within their science classes, activities to foster SRL and conceptual development. Further, as part of this, the students and teachers had four to five sessions of training in collaborative group work.

Phase two took up the largest amount of time and included the main activities planned within the context of the project. It involved learning and assessment activities through collaborative group activities and discussions in the classroom, and individual assessment activities for the children selected as cases outside of the classroom. It is important to stress that these assessment activities were thought to also promote learning through the assessment and therefore to become an integral part of the learning process. During this phase, observations of regular classroom activities were also planned in order to describe some characteristics of the learning

[1] See Grau (2008) for the complete research study.

environment and to observe the children while they were working in regular science classes. Thick data was collected for each case in order to track the development of self-regulated learning and biological concepts.

The presence of the researcher as an assistant in several classroom activities during this phase was also a way to support the teachers, helping them to observe the thinking and learning processes in their students. The scientific contents taught and evaluated were related to biological scientific concepts specified in the Chilean curricula and included the general notion of photosynthesis, classification of living things and basic interactions between living things and the environment.

In addition to these classroom group work activities, the children selected as cases were involved in individual assessment activities. The photosynthesis concept was assessed through an interview which explored the ideas that children had in relation to plant food. Therefore, it was a rather direct interview seeking to obtain declarative knowledge (i.e. how do you think the plant grows?). The interactions between living things and environment interview had different characteristics. In this case, children were asked to use knowledge to think in hypothetical situations (i.e. what would happen if all the plants in the world died?). The classification of living things assessment consisted of a sorting task, in which the children were asked to sort cards with animals and plants using any criteria to make groups of things that 'belonged together'. This activity was not based on asking many explicit questions but mainly on the explanation for the sorting criteria after the resolution of the task. All these activities were videotaped.[2]

Finally, during Phase three, a final individual and group assessment of the cases was carried out regarding self-regulated learning and conceptual development. Also, interviews were carried out with the science teacher involved in the project in order to collect information regarding her perceptions of the children selected as cases and the teaching and learning activities.

Data Analysis

The data analysis was carried out using qualitative and quantitative techniques with the objective of producing rich descriptions and triangulating the data, as described in the following paragraphs.

For the assessment of conceptual development, scoring systems were created for the three concepts evaluated, generating rubrics[3] for each of them with five levels of achievement. Therefore, the scores were discrete categories ranging from 0 to 4, where 4 represented an understanding aligned with the scientific definition of the

[2] See Appendix 1 for details of these tasks and the questions used to explore children's understandings in relation to them.

[3] A rubric is a scoring tool for subjective assessments. It is a set of criteria and standards linked to learning objectives that is used to assess a student's performance on papers, projects, essays and other assignments.

concept. Also, thematic analysis of the children's answers was conducted in order to characterise the development of understanding in each child.

In the case of self-regulated learning, the main analysis was carried out through the development of a coding framework to observe and code the children's behaviours video-recorded when they were working in the collaborative groups in the biological science classes and individually in the photosynthesis, interactions between living things and environment and classification of living things assessment activities. This framework defined the events which were taken as evidence of regulation of cognitive, affective and social processes, and the main codes referred to planning, monitoring, control and evaluation of different aspects of the activity.[4] Afterwards, frequencies of self-regulated learning behaviours per child were calculated.[5] Finally, the interviews with the children regarding their metacognitive knowledge and reflection ability in relation to their work were also analysed in order to find the main themes and meanings within their discourses.

Having carried out these analyses with regard to conceptual development and self-regulated learning, a profile of each case was constructed, and a cross-case analysis was carried out. This cross-case analysis showed a configuration in which three different groups emerged taking into account their ranking in seven different types of analysis of SRL assessments (including individual and group behaviour and verbal report through interviews), based on the system presented by Hadwin et al. (2004). In this procedure, 'High SRL' were the children who were qualified as 'High' in at least five of the seven measures of SRL, 'Low SRL' children were qualified as 'Low' in at least five of the seven measures of SRL and classified as 'High' in none and 'Medium SRL' was the group which showed a more mixed pattern, with 'High', 'Medium' and 'Low' results in different analyses. Table 6.2 provides details of the indicators used to group the students in this way.

Individual Level: Overall Comparison Between Evaluations of Self-Regulated Learning and Conceptual Development

Having brought together different types of evidence of conceptual development and self-regulated learning across cases, an analysis was conducted regarding the relationship between both constructs (see Table 6.3). Are the children exhibiting higher self-regulated learning skills showing greater evidence of conceptual development or vice versa? The data did not provide straightforward answers or at least, not a simple relationship between these constructs; however, some interesting suggestions could be extracted from the data.

[4] See Appendix 2 for the SRL coding schemes used within the study.

[5] Kappa coefficient between two coders of the individual SRL coding scheme was 0.94; of the group work coding scheme, 0.92.

Table 6.2 Sets of data/types of analysis and indicators used to classify the case study children as High, Medium or Low in SRL

Data set per child	Analysis conducted	Indicators for the grouping
Individual assessment: videotaping of children while solving an individual task and interviewing afterwards	Coding of on-line events of planning, monitoring, regulation and evaluation while carrying out the task. Frequencies were obtained	(1) Frequencies of on-line regulation and ranking of the students in relation to those frequencies
	Coding of events evidencing reflection and evaluation in relation to the task during the interview after the activity. Frequencies were obtained	(2) Frequencies of reflection and ranking of the students in relation to those frequencies (3) Total frequencies of SRB and ranking of the students in relation to those frequencies
	Thematic analysis of children answers, looking at evidence of reflection and evaluation of their own work	(4) Overall categories of High, Medium or Low quality of reflections
Assessment of children while working in groups	Coding of on-line events of planning, monitoring, regulation and evaluation. Rates were obtained	(5) Total rates of SRB in groups and ranking of the students in relation to those rates
	Coding of events when 'shared regulation' events were accomplished. Rates were obtained	(6) Total rates of SRB directed to the shared regulation of the task and ranking of the students in relation to those rates
	Coding of events when children were regulating fundamental aspects of the task, looking at the final goal instead of only practical aspects. Rates were calculated	(7) Total rates of SRB related to fundamental aspects of the task and ranking of the students in relation to those rates

Table 6.3 Cross-SRL group comparison according to different types of evidence of CD

SRL group	Classification	Photosynthesis	Interactions
High	Positive: the children exhibited a very good performance in the classification task regarding quality of categories, strategy use and reflection regarding the task	Negative: the children had the lowest performance compared with the other groups	Positive: the children had the highest performances compared with the other groups
Medium	No clear relationship	Negative: the children had the highest performance compared with other groups	No clear relationship
Low	No clear relationship in quality of categories Positive: reflection regarding the sorting task was very poor	No clear relationship	Positive: the children exhibited the lower quality answers

First of all, self-regulated learning and conceptual development were not manifested through the analysis as unitary concepts. The children showed great variability across the analysis of different evaluations of self-regulated learning and conceptual development. However, self-regulated learning seemed to be a more consistent characteristic, as it was possible to identify some children who more consistently exhibited self-regulated learning behaviours through the different assessment activities. The case of conceptual development was more difficult as the variability appeared to be pronounced, suggesting that at least for these children, knowledge regarding biological concepts was not necessarily interconnected in their understanding and had to be evaluated and analysed as discrete areas of knowledge. So, for example, some children who showed high ability and understanding in relation to classification of living things performed relatively poorly in relation to their understanding of photosynthesis.

Taking these considerations into account, we will now come back and examine which aspects of the relationship between self-regulated learning and conceptual development in these eight cases seem to be revealed through the data from the cross-case analysis and the commonalities found among the members of the same self-regulated learning group. All the evaluations of conceptual development are included in this comparison. Table 6.3 summarises some suggestions of the types of relationship that could be extracted from the data. This shows whether there is evidence suggesting a positive or negative relationship between self-regulation and evaluations of conceptual development. It is described as positive when a particular set of data suggest a positive relationship, implying that both factors go in the same direction (e.g. high SRL, high CD), and negative when the data suggest an inverted relationship (e.g. high SRL, low CD). We can see from the table that the majority of the clear relationships come from the 'High' SRL group as it is the most homogeneous group. It is more difficult to discern relationships from the data of the 'Medium' group as a whole, since there is too much variability within the group.

Regarding the *classification of living things task*, there are a number of interesting points to note. First of all, the findings regarding the 'High' SRL group suggest that the children who were found higher in self-regulated learning tended to improve and obtain high scores in this task. Figure 6.1 presents data from a case in the 'High' SRL group demonstrating a high level of performance and self-regulatory skills. However, there is no consistent evidence in the lower groups. Figure 6.2 presents data from a 'Low' SRL case. The children in the 'High' group also seemed more strategic and presented outstanding levels of reflection, while the children in the 'Low group' presented poorer reflections.

The classification of living things task has particular characteristics as it involves some knowledge – which is not evaluated in a declarative form – and skills combined. Therefore, the data obtained through the observation of this task is evidence of conceptual understanding while, at the same time, regulatory skills. For this reason, it is also difficult to distinguish between the two constructs. However, the data suggest that at least when the children exhibited high levels of self-regulation, they tended to perform at a higher level in the classification of living things task in

CLASSIFICATION OF LIVING THINGS TASK 1: Beginning of academic semester

He makes 5 groups: vegetables, insects, animals, plants, domestic animals.

In the interview he seems very much aware of the way he solved the task and metacognitive knowledge about his classification strategy: *'I... when I want to make a group I do this, for example, the caterpillar, I see it and I have to make a group of what it is... I see and I create a group of what I see and if there are not too many and I do it wrong, I put them together with another or I re arrange them'.* He makes clear connections between his way of classifying and the science classes *'In kindergarten I learned that when the plants are cut they don't live anymore'*

CLASSIFICATION OF LIVING THINGS TASK 4: End of academic semester

He makes the following groups: animals covered by skin, animals covered by hair, animals with scales, felines, plants, animals covered by feathers, insects.

He again tells in detail how he came up with the groups he did. He showed awareness and reflection about what he did and metacognitive knowledge about what he knew from previous experiences: '*The first one I saw was the fly, therefore I had to think 'a fly, which one could go with' and I put the fly down apart. Then I found another very different from the fly, for example, the iguana, they have nothing in common (…) and I could make different groups with both, and I knew that a lot more were coming, such as the cricket and the caterpillar...'*

He is aware that it was a bit difficult to think in the groups. It seems that this time he has different possible ideas '*I found one and gave me one idea and then, for example, I found this one and it has feathers, but the group had just 2 cards and it had to be a bit bigger...'*

Fig. 6.1 Case from the 'High SRL' group: performance on the classification of living things task

CLASSIFICATION OF LIVING THINGS TASK 1: Beginning of academic semester

She sorts them in the animals that swim, animals that fly, animals that jump, animals that walk, the ones that are planted in the soil (referring to plants), and the ones that move.

In the interview, her strategies of looking at the cards and then creating the groups as the animals were appearing in the pile seems coherent with what was observed when she was doing the task. However, she started very quickly to sort them through transportation patterns and she did not change cards, suggesting that once she thought in the criteria, she did not think about that anymore.*'I thought... if there was that jumped if there were others that jumped as well, others that were planted, the ones that walked (…) after looking at them'.* She does not verbalise further reflections on her performance.

CLASSIFICATION OF LIVING THINGS TASK 4: End of academic semester

The groups she made are: animals that walk, animals that jump, animals that crawl, animals that swim, animals that fly and the ones that stand still and are eaten (plants).

In the interview she says that she had to think what to do and that it was a bit difficult to decide what groups to make. However, that is not very well reflected in the way she did: she looked very clear about what she was doing especially considering that she is using almost the same categories that she has used all the other evaluations. She was vague in her verbalizations *'All the things I had in my mind I put them here (…) I looked at them first and I thought in putting them this way'.*

Fig. 6.2 Case from the 'Low SRL' group: performance on the classification of living things task

all its aspects: quality of categories, strategy use and reflection. No clear evidence, however, could be found of a direct relationship between the level of self-regulated learning and the performance in this task with children belonging to 'Medium' or 'Low' SRL groups.

Considering the case of the *photosynthesis* interview, more puzzling findings emerge: the children with 'High' levels of self-regulated learning were the children who performed the least well in the photosynthesis interview. The highest scores belong to those in the 'Medium' SRL group. Figure 6.3 shows the conceptual trajectories of the eight children studied as cases: the two children who were not able

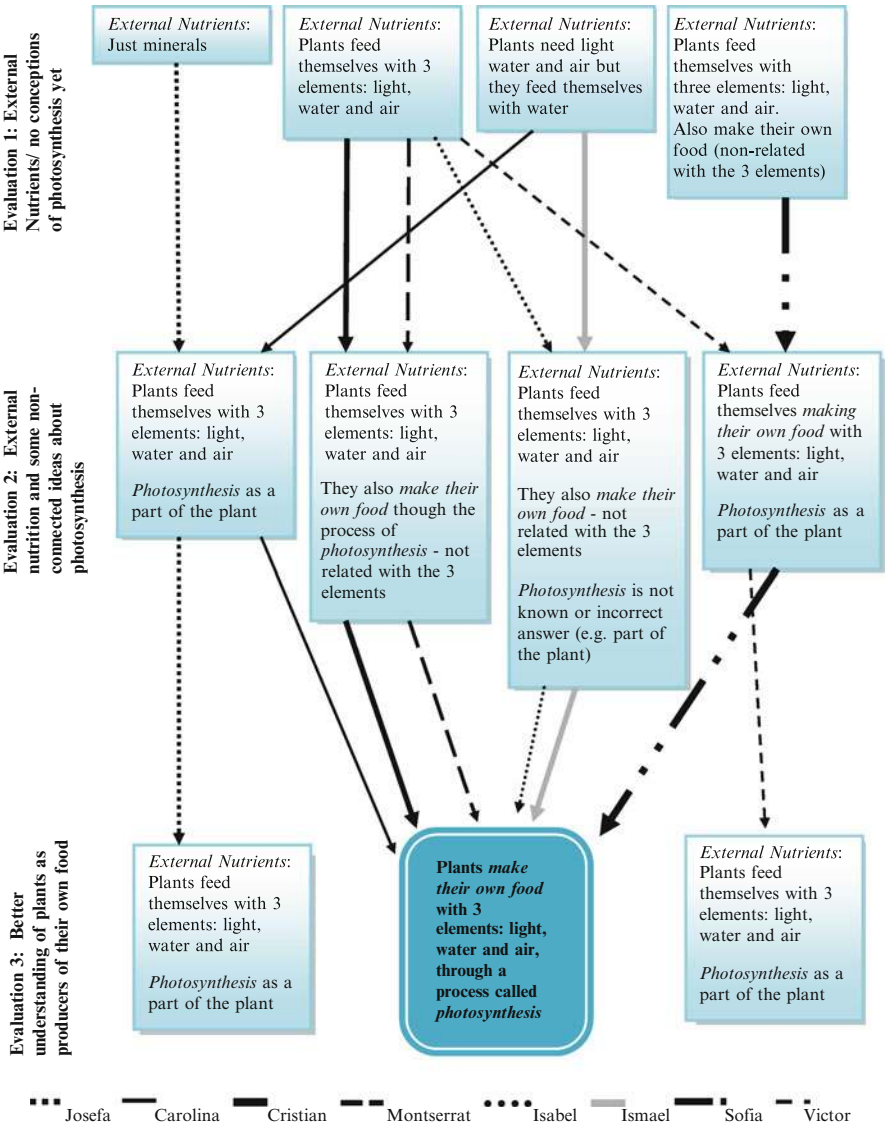

Fig. 6.3 Individual trajectories in the development of the photosynthesis concept

to enunciate the correct answer in the last evaluations were those qualified as the 'High' SRL group.

Despite the analysis of the photosynthesis interviews in relation to SRL, it is interesting to observe the wide range of variability reflected in children's answers, especially at the intermediate states: while some children had trouble understanding photosynthesis as a process, others struggled with understanding that the plant makes its own food. Moreover, some children kept two different conceptions that

were not consistent between each other. These findings are consistent with previous research in the field, as reviewed in the section concerning learning in the biological domain. Nevertheless, it is surprising that most of the children had a very similar level of comprehension at the end of the semester and they demonstrated a better grasp of the main concepts involved in the process of photosynthesis.

And yet another pattern of development is observed when we look at the results of *the interaction between living things and their environment interview*, in which the relationship between self-regulated learning and conceptual development seem to be more clearly positive: the children belonging to the 'High' SRL group displayed the most sophisticated answers in the interview in comparison to the other cases, whilst, in turn, the children belonging to the 'Low' SRL group exhibited the poorest answers. For example, in the last interview, to the question asking what would happen if all the plants disappeared, the students responded as follows:

'High' SRL: 'The absence of plants would affect herbivores in terms of food, but they would also be missed as a source of oxygen and shelter for some animals'

'*Low' SRL*: *'Plants give oxygen, that is why animals need them'*

and in relation to the question about the relationship between plants and animals, the following answers were recorded:

'High' SRL: 'Animals could help plants to reproduce (like the case of bees) and animals give plants carbon dioxide they need'

'Low' SRL: *'I don't know'.*

Therefore, there seem to be different relationships between conceptual development and self-regulated learning depending on which kind of knowledge we are evaluating and the kinds of tasks we are using to evaluate that knowledge. It is not surprising that the children who showed high self-regulated learning skills across tasks performed better in evaluation tasks that actually required higher level thinking skills such as the classification of living things task and the interactions between living things and environment interview. The classification of living things task required mainly on-line regulation, ability for planning, monitoring, controlling and evaluating their work and use of knowledge to solve a practical task. The interaction between living things and environment interview also required self-regulated learning but rather as it affects the ability to make inferences in hypothetical situations in relation to knowledge. Thus, in this task, the children had to think and evaluate the possibilities regarding the questions presented by the researcher. The photosynthesis interview, by contrast, was rather based on the direct reproduction of declarative knowledge, so that children mostly needed to recall information from memory rather than solve a problem. Taking this into account, it is perhaps not so strange that the children in the 'High SRL' group performed better on the tasks that demanded more advanced self-regulation skills.

Group Level: Socially Shared Regulation of Learning

Special categories of planning, monitoring, regulation and evaluation codes were created to analyse the self-regulated behaviours (SRBs) within the group work activities. Each of these categories was further coded according to two modifiers: direction of the activity and social aspects. The modifier 'direction of the activity' indicated whether the regulating behaviours shown by children were mainly directed to (a) fundamental aspects of the task (talking about the goal of the task or fundamental knowledge required to solve the task), (b) practical aspects of the task (e.g. which materials they were going to use), (c) organisation of the group work necessary to reach their objectives or (d) socio-emotional aspects of the group work.[6]

The analysis of the two groups of four children showed that most of their SRBs were directed to practical aspects of the task (around 50%), around 20% related to group work organisation activities and smaller percentages to fundamental aspects of the task and socio-emotional issues.

The social modifier, in turn, qualified the SRBs in terms of the social direction of the child's intervention and indicated whether it was intended to regulate himself/herself (self-regulation), regulate asymmetrically another member(s) of the group (co-regulation) or regulate the joint activity as part of a symmetrical communication of ideas (shared regulation).[7]

The most commonly observed behaviours were directed to co-regulate a classmate (around 44%), followed by shared regulation (around 36%). The least frequently observed was self-regulation isolated from the group (around 20%), presumably because the context prompted regulation behaviours related to others.

When the frequencies of the two modifiers were correlated, there were significant correlations between rates of SRBs directed to shared regulation and SRBs directed towards fundamental aspects of the task (Spearman rho = 0.741, $p < 0.01$). In other words, those children who tended to have higher rates of SRBs related to regulating the joint group work activity with an emphasis on symmetrical collaboration also tended to have higher rates of SRBs directed to regulate fundamental aspects of the task. This was especially the case when those fundamental aspects were related to the discussion of the necessary knowledge which needed to be applied to solve the problem within the activity.

Returning to the cross-case analysis, what emerges is that the children belonging to the 'High SRL' group appeared during the group work activities as the most advanced in terms of the level of discussion they could sustain. They had the highest rates of statements directed to 'shared regulation', and one of them (Victor) had also the highest rates of statement directed to fundamental aspects of the task. In contrast, the children belonging to the 'Low SRL' group presented the lowest rates of shared regulation and statements directed to fundamental aspects of the tasks, respectively. The

[6] Kappa coefficient = 0.9.

[7] The Kappa coefficient between the two coders for this modifier was 0.78.

'Medium SRL' group tended to present average rates of SRBs in the group work activities. This pattern of results would seem to suggest that there was a clear positive relationship between the general pattern of SRL exhibited by the children individually and the SRBs shown during the group work activities. The dialogue below was extracted from a conversation involving Josefa and Victor, both from the 'High' SRL group, regarding the creation of a diagram of photosynthesis during a group work activity. It is characterised by having several utterances relating to fundamental aspects of the task and shared regulation of learning. In this case, Josefa seems to have had an insight concerning the fact that the main processes related to photosynthesis (light and oxygen capture and making food) happen in the leaf, so she is suggesting they change the original idea of making a plant with a flower to just making the leaf:[8]

Josefa: I think we could make a leaf instead, not the *whole* plant, roots, petals and stem, only the leaf… (*She suggests her new idea to the group)*
Isabel: No, let's make a flower like this (*She wants to keep the original idea*)
Josefa: well, OK (*a little disappointed*)
Isabel: (to another child) you, draw the sun! (*She starts giving orders but she realises that Josefa is not sure about the flower idea*) OK, let's make a leaf (to Josefa) (*She seems uncomfortable with the disagreement*)
Josefa: Victor, what do you think? Is it better to make the whole plant or just the leaf like this? Because I think that maybe only the leaf is necessary and we would also use less plasticine. (*She does not seem uncomfortable with the discussion, she seems willing to have an agreement and not only do her idea, therefore she asked the opinion of Victor*)
Victor: But what do we have to demonstrate? In which way the plant makes its food? (*He refers back to the aims of the task in order to analyse the situation*)
Josefa: Yes, that, how it makes its own food, there is glucose
Isabel: Let's just make the leaf (*uncomfortable with the discussion, she seems impatient to move on and carry out the task*)
Victor: Yes but with the leaf we could not demonstrate how is the process in the stem, the roots… (*Arguing that other parts of the plants are also important*)
Isabel: And she says that we just have to make a leaf! (*Now she changes her mind based on Victor's opinion*)

This piece of dialogue shows how Josefa was monitoring the activity and thinking that there could be a better way of doing the photosynthesis diagram. At the same time, she was willing to share her ideas and receive reasonable feedback about the best way of carrying out the task. In this sense, she exposed her ideas and asked for explicit opinions from another member of the group, when this could be actually rather intimidating for a child exhibiting a rather performance-oriented approach. Victor, in turn, engaged in her discussion and shared his opinion trying to create a group discussion when he referred back to the objectives of the task before making a proposal.

[8] The words in italics are the researcher's interpretation of the utterance.

In fact, the clear majority of these 'shared regulation' episodes were prompted by these 'High' SRL children. This shows the essential interest shown by these children in trying new alternatives and their flexibility and openness to external critiques in order to produce better quality work. This is coherent with findings reported in relation to university students and brings us back again to the less researched motivational and relational issues regarding self and social regulation of learning SRL (Volet et al. 2009; Kimmel and Volet 2010).

Discussion and Concluding Remarks

In this study, a range of evidence of self-regulated learning and conceptual development was brought together in order to shed light on the relationship between both constructs in these eight cases. The cross-case analysis highlights the great extent of variability found across cases that basically were from the same age group belonging to the same context in the same classroom. This finding demonstrates the great variability between children in learning and development and gives relevance to the study of the process of learning, instead of only the products, as claimed by researchers from the microgenetic perspective (Lavelli et al. 2006). Further, the evidence from this analysis did not suggest a clear linear relationship between self-regulated learning and biological knowledge as a unitary concept. It would seem that this relationship has to be analysed considering the different kinds of knowledge or sub-domains considered in this research. This detailed analysis indicated that children who belonged to the 'High' SRL group tended to perform at a higher level in terms of the different aspects of the classification of living things task and interactions between living things and environment but not in the photosynthesis interview. This suggests that, at least at the beginning of the process of knowledge construction in this particular domain, children could demonstrate knowledge or skills in one sub-domain and not in another (e.g. knowledge about photosynthesis but not understanding the relationship between animals and plants). Even in the case of the same sub-domain (e.g. photosynthesis), declarative knowledge might not necessarily correspond with skills, as children at this age are not always able to explain their understanding of the world.

A further important contribution of the present study has to do with the methodology used for looking at children's self-regulatory activities within a group and the incorporation in the analysis of the modifiers, which provided the most interesting data in terms of explaining individual differences. Especially relevant are the correlations between shared regulation and fundamental knowledge, which is clearly suggestive of a relationship between fundamental aspects of the task, such as goals and knowledge, and SRL. Also, the fact that the children from the 'High SRL' group also appeared more intellectually adventurous, willing to share their ideas and actively initiating high-level discussions within the groups is also very relevant.

It could be hypothesised that, at least within the cases studied in the present research, the main difference that distinguished the 'High' SRL group from the

others arose from the motivational characteristics and degrees of reflection presented by the children belonging to this group. They were not very knowledgeable at the beginning of the semester, but they were reflective and highly motivated to learn. These factors could be a powerful engine to develop self-regulated learning skills and conceptual development. This finding relates interestingly to the construct of 'intentional conceptual change', when Sinatra and Pintrich (2003) describe intentional learners not only as cognitively engaged in their learning processes but also being influenced by the motives, goals, beliefs and emotions being brought to the learning process. Moreover, returning to Limon's (2003) model of the relationship between SRL and intentional conceptual change, it is interesting to note that she emphasises self-regulation as a pre-requisite for ICC. This consists of being aware of learning processes and resources (as shown by the high levels of reflections shown by children in the 'High SRL' group) and the regulation of their emotions, motivations, interest and strategic skills (also shown by the 'High SRL children').

Limon (2003) further hypothesised that when there are high SRL skills but low domain-specific knowledge in a domain – as in the case of these children – the SRL skills would be difficult to transfer from one domain to the other; that the transferring of SRL would be influenced by the task and its similarity with the tasks in which the learner developed his/her SRL skills and that individuals might be more able to reflect on what they need in order to learn. As we have shown in the forgoing analysis, the findings of the present study tend to be aligned with these hypotheses.

As regards to general science education and other domains of knowledge, the advantage of fostering self-regulated learning in all its aspects is clearly supported by the present study's findings. This is particularly interesting in science education because it is a discipline where it is necessary to experiment with the world in order to learn. This requires motivational, emotional and social skills in addition to purely cognitive abilities. In terms of a general teaching approach, we would argue that the evidence from the present study would support what has been called an autonomy-supportive teaching style (Reeve et al. 2008; Reeve 2009). This relates to certain instructional behaviours such as the nurture of students' inner motivational resources, the provision of explanatory rationales, the allowance for self-paced learning and the acknowledgement and acceptance of negative affects.

From the experience of this study, it seems clear that classroom activities, such as group work challenges, or open activities, such as the classification of living things task, give children the opportunity to develop their self-regulation skills and dispositions. Importantly, they also promote the enjoyment of learning in science. In turn, this kind of approach seems more fruitful in relation to developing strong mastery-oriented motivation, a desire to learn powered by the need for understanding, in relation to science learning among our students. These are important educational goals and ones which present a clear challenge to our educational systems.

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Appendix 1

Children were evaluated individually several times during the semester regarding the three core concepts chosen to focus on the intervention: classification of living things, photosynthesis and interactions between living things and their environment. The objective of these tasks was to have a deeper understanding of children's conceptions, having the opportunity for asking for clarifications and exploreing the limits of children's knowledge in that subject matter.

Classification of Living Things

This task is based on the research of Panofsky, John-Steiner and Blackwell (1990), who developed this task in order to assess scientific concepts in primary school. For designing the task, they considered that the activity should be appropriate to be worked at schools, but not test-like. Therefore, they designed a task open to several solutions, to be solved through different possible strategies.

The procedure was the following: Children were asked to carry out four classification tasks during the academic semester. The first session had an easier task at the beginning to make children more comfortable. They were given a set of 13 pictures, 5 of plants and 8 of animals and they were asked to sort the pictures in two piles, and explain why those items belonged together. Then, the children were given a second set of 34 living things (13 from the first set plus 21 more) and they were told that they could sort the pictures in as many groups as they wanted, but no fewer than 3. Afterwards, they had to explain the grouping criteria to the researcher.

From the second sorting task, the children had to carry out only the classification with the 34 living things following the same instructions. After each sorting task the researcher asked the children some questions regarding how they sorted and classified the categories and carried out the activity to obtain some evidence of verbal reflection regarding cognitive and metacognitive strategies, metacognitive knowledge and motivation. As a semi-structured interview, some questions were added to the list presented below in order to clarify some of the answers provided by the child. The basic questions were:

- What was the main thing that you had to do in this activity?
- How did you solve the task?
- Was it difficult to understand what you had to do? (Only the first time)
- Do you think that the things you have been working in science classes have helped you to solve the task?
- Did you plan anything in your head before to solve the task? Or you were just doing the things at the same time you were thinking?
- How well you think you did?
- Do you think that you made any mistake?
- How did you feel while you were doing the problem? (Interested, bored, anxious, relaxed)

Plants as Producers of Their Own Food: Photosynthesis

This assessment was conducted three times during the semester: at the beginning of the year, right after they reviewed the concept of growing plants and photosynthesis in the classroom, and at the end of the intervention.

During the first evaluation, children were asked several questions regarding the plant, with the objective of detecting whether children had a basic conception of plants as living things. The interview was carried out having a real plant in front of the child. The questions were: Can it see? Can it hear? Does it eat? Does it breathe? Does it have babies or lay eggs? Does it need water? Does it live forever?

After the first set of questions, the researcher asked more specific issues regarding plants' food:

- Do you know how the plant grows?
- What is the food of the plant?
- Have you heard about the concept of photosynthesis?
- What would happen if we take all the leaves out of this plant?

This set of questions was repeated another two times during the semester. The first set of questions was not repeated again, given that the children answered them correctly on the first interview, suggesting that they did have a fairly clear idea that plants were living things. The second set of questions was repeated on the second and third evaluation and, depending on the answer of the child, the researcher asked more questions to clarify the answers. For example, if the child said that the plant makes its own food, further questions could be asked such as, how does it do it? Which kind of food? etc.

Interaction Between Living Things and Their Environment

This assessment was conducted two times during the semester: at the beginning of the year, and right after they saw the concept of interaction of living things and their environments in the classroom, which coincided with the end of the semester.

The children were given a colourful picture of a habitat, with several plants and animals living there and they children were asked to look carefully at the picture and describe what they see. Afterwards, a semi-structured interview was carried out. The main questions were the following:

- Do you think that those animals need to live together or they could live separate from each other? Why?
- What do you think would happen if all the plants in the world died? Why? If the children did not say anything, another question was prompted: Do you think that the animals would be affected by that? Look at your picture and imagine what would happen without the plants.
- What do you think it would happen if all the animals disappear? Would that affect the plants? Why?

Appendix 2: Coding scheme for SRL

SELF-REGULATED ACTIVITY	PLANNING	MONITORING	REGULATION	EVALUATION
Area of development	Reasoning/decision making/initial appraisal of the task	Awareness and monitoring of various aspects of cognition, beliefs, affects and motivational states	Selection and use of various cognitive strategies for learning, reasoning, memory, thinking, motivation and emotion. It comes after monitoring of the task	Involves learners' judgement, evaluation attributions and emotional reactions to their performance
Cognitive	• Activation of relevant prior content knowledge • Activation of metacognitive knowledge • Target goal-setting The child: – Talks about the relevant content knowledge to be applied in the resolution of the task – Talks about his/her knowledge about strategies or personal resources that can be used in order to solve the task – Talks about setting goals – Establishes task-specific goals that can be used to guide cognition and monitoring – Propose a way of solving the task *Examples* *'I will look at all the cards first and then I will decide how to make the groups'*	• Judgements of learning • Comprehension monitoring • Feeling of knowing • Rating performance • Checking behaviours The child: – Talks about his/her understanding of the task – Talks about things that he/she knows but does not remember – Checks the progress of the task – Detects errors – Uses his/her content knowledge to help the monitoring of the task *Examples* *'I knew what photosynthesis was, but I can't remember now'* *'The teacher told us that in the lesson, but I don't know'* *The child checks each group he/she created in the sorting task*	• Learning strategy use • Error detection/strategy change • New idea for solving a problem when the one being used seems to be ineffective The child – Uses appropriate strategies: solving problem, seeking help, using self-speech for helping performance – Changes strategies that seem to be less effective *Examples* *The child finds a card with an animal that does not fit in any of the groups and he decides to re-organise the categories*	– Evaluation of the work done in relation to goals – Evaluation of the effectiveness of the strategies The child • Evaluates the quality of performance *Examples*: *'I think I didn't do well because I did not know where to put this one'* *'I wanted to make carnivores, herbivores and omnivores, but I was not sure what each animal ate'*

(continued)

(continued)

SELF-REGULATED ACTIVITY	PLANNING	MONITORING	REGULATION	EVALUATION
			Selection and use of various cognitive strategies for learning, reasoning, memory, thinking, motivation and emotion. It comes after monitoring of the task	Involves learners' judgement, evaluation attributions and emotional reactions to their performance
Area of development	Reasoning/decision making/initial appraisal of the task	Awareness and monitoring of various aspects of cognition, beliefs, affects and motivational states		
Motivational emotional	• Perceptions of the value and interest that the task has for them • Perceptions of their personal interests in the task or in the content domain of the task • Judgements of self-efficacy/easy to learn judgements • Goal orientation The child: – Talks about how interesting (or not) is the current task for him/her – Talks about his/her own feeling of being capable of solving the task – Comments on how important it is to learn or to obtain a good performance *Examples*: *Not found*	• Awareness of motivational state, affects and self-efficacy beliefs The child: – Comments on his/her motivational/emotional state *Examples*: *'I am bored'* *'I like to come here so I can be away from the classroom'*	• Strategies for controlling motivation • Self- encouragement • Positive: positive self-talk, external reward *Examples*: *Not found*	Feeling regarding the work – Attribution of success or failure The child: – Talks about/shows feelings regarding the task – Talks about the reason for success or failure *Examples*: *'It was fun'* *'It is good that this does not have a grade'*

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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

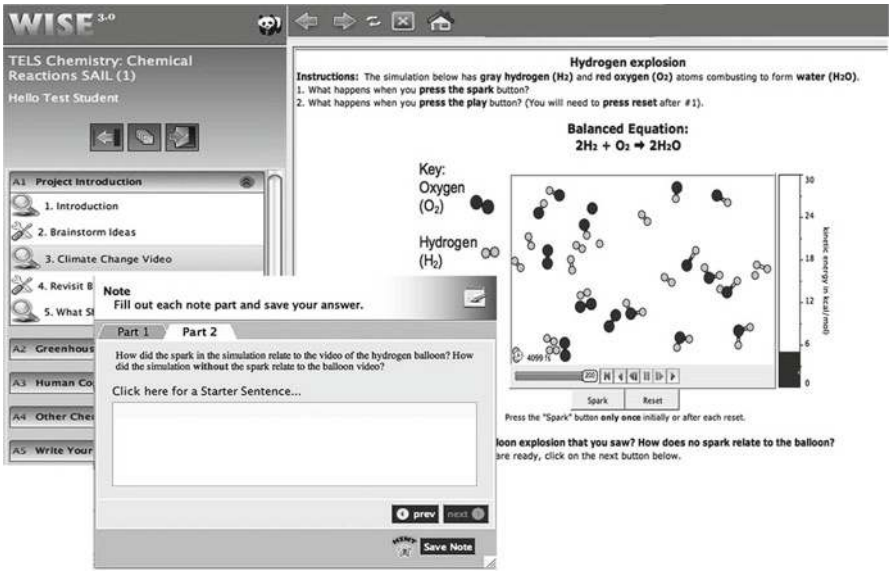

Fig. 7.1 In the WISE *chemical reactions* project, students use the inquiry map on the left to guide inquiry, use visualizations to add and test ideas, and use pedagogical tools such as online discussions, drawings, and embedded explanations to help distinguish ideas

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

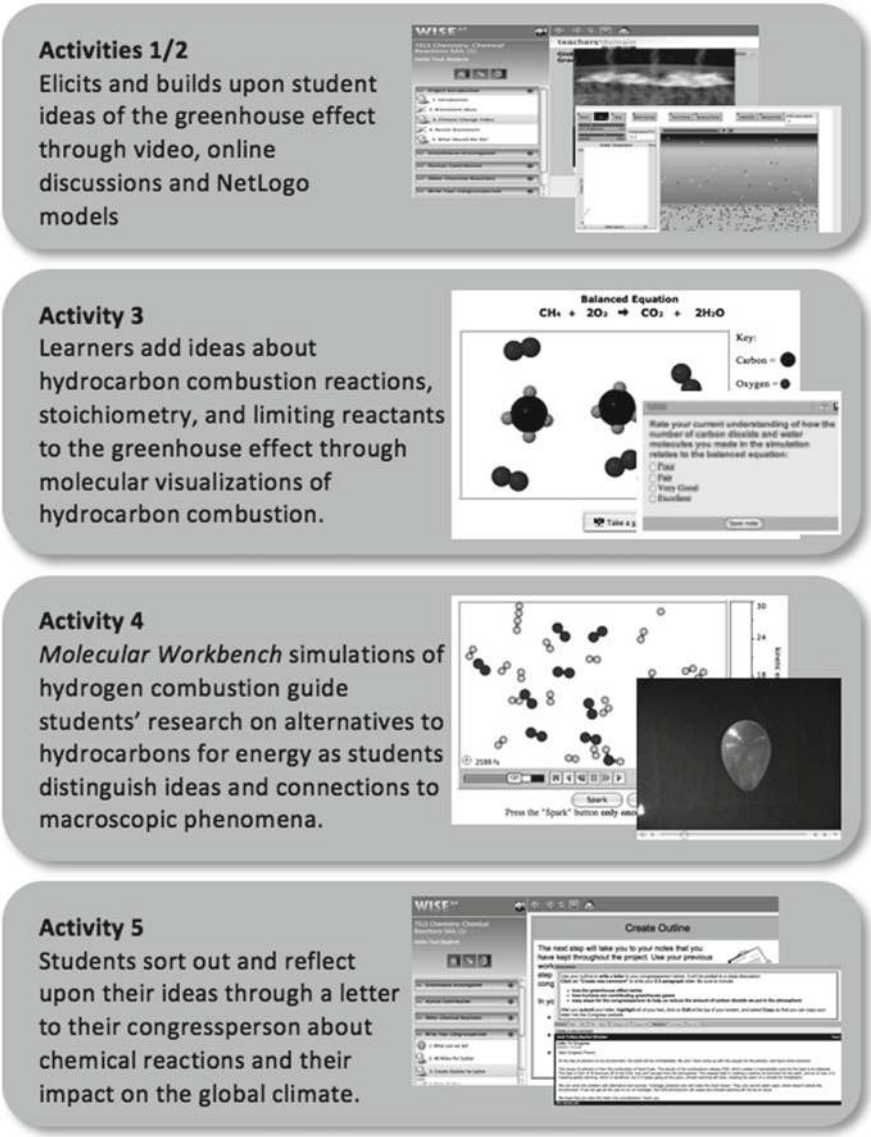

Fig. 7.2 The different activities within the *chemical reactions* project guide students along the knowledge integration pattern

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

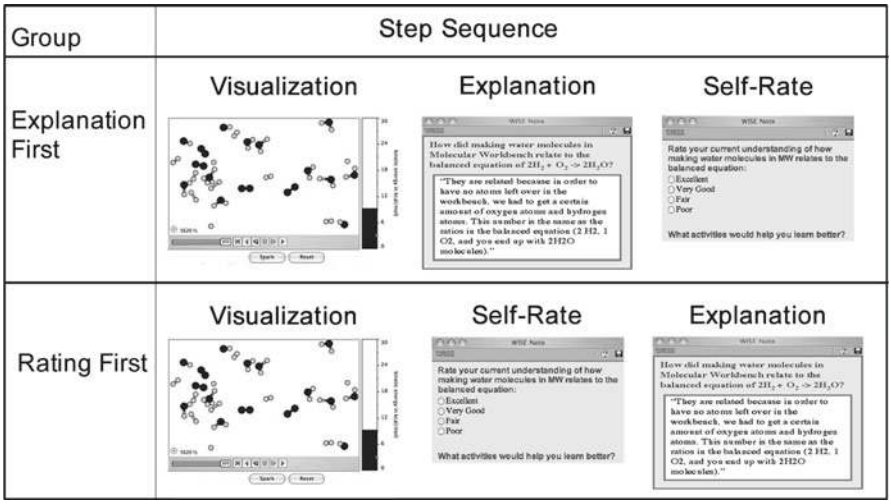

Fig. 7.3 In the judgment of learning study, the Explanation First group explained their understanding immediately after working with visualizations, and the Rating First group rated their understanding immediately after interacting with visualizations

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.

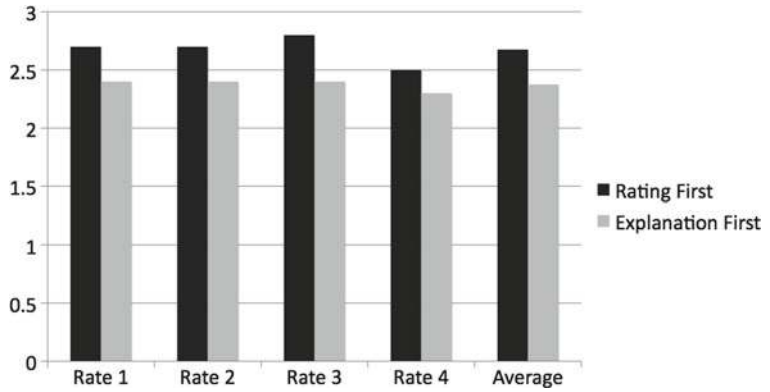

Fig. 7.5 Self-rating scores by Rating First and Explanation First group for each self-rating prompt and overall rating

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

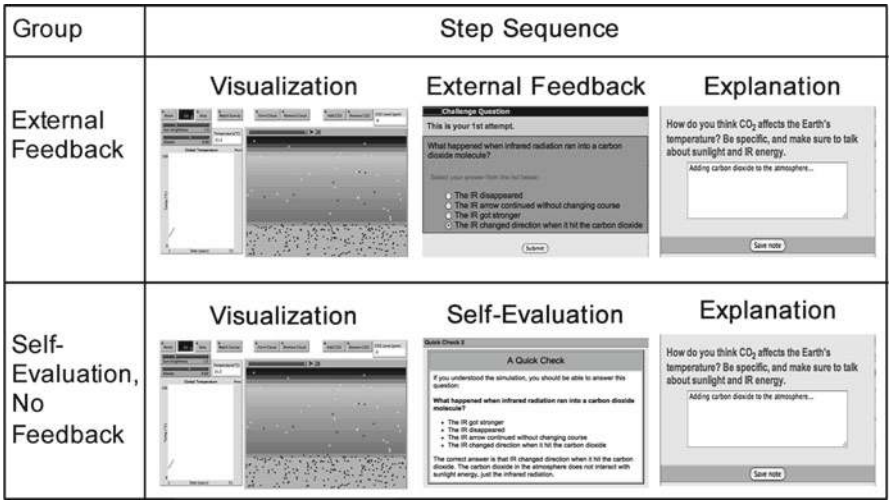

Fig. 7.6 External Feedback and Self-evaluation No-Feedback conditions for revisiting study

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

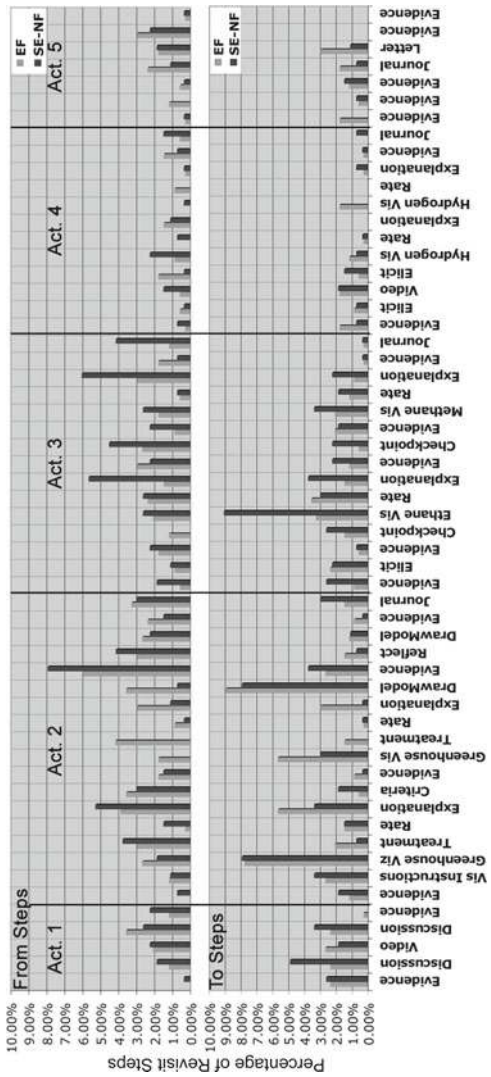

Fig. 7.7 Timeline of student revisits in the revisiting study. The top graph displays the steps from which students revisit for each treatment, and the bottom graph displays the steps to which students go when they choose to revisit a step

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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Chapter 8
The Relationship Between Metacognition and the Ability to Pose Questions in Chemical Education

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Introduction

Educating high school chemistry students to adopt new thinking and metacognitive skills is a complex and demanding task. It requires the development of new teaching strategies and, in most cases, changing teachers' and students' roles and often also their beliefs. Question posing is a higher-order thinking skill, and as such it is linked to metacognitive knowledge. This chapter describes two related studies which investigate the effect of exposing high school chemistry students to metacognitive tools and strategies involving the question posing skill while reading adapted scientific articles and case studies. In this chapter, we define adapted scientific articles as articles which are based on scientific articles that are mostly from secondary sources. These sources, in turn, are based on primary sources – original scientific research articles.

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The first study investigated the ways by which the knowledge about strategies affected high school chemistry students' skills to pose complex questions and to analyze them according to a specially designed taxonomy in the *case-based computerized laboratories* (CCL) environment. Students were asked to pose questions after reading an article and then assess the quality of their questions according to a given classification. The objective of the second study was to investigate the effectiveness of a self-developed metacognitive tool for high school chemistry students' comprehension of adapted scientific articles.

Presenting the objectives, the metacognitive tools, participants, settings, methodologies, and findings of these two related studies, this chapter sheds light on the relationship between metacognition and the ability to pose questions in a case-based or adapted article learning environment. Although our studies were conducted in the context of chemical education, the metacognitive tools we have developed and the ways they are used can be modified and implemented in other science domains.

Background – Reforming the Chemistry Curriculum in Israel

The beginning of the twenty-first century is marked in many countries by reforms in science education in general and chemistry education in particular. In Israel, both the content and pedagogy of chemistry curriculum have been reviewed and modified. The most dramatic change that has been introduced into the chemistry curriculum in Israel is the engagement of advanced chemistry students in laboratory activities, reading case studies and adapted chemical articles, and embedded assessment.

Since the early 1950s, Israeli high schools have been accustomed to preparing their students to pass the national matriculation examinations. Therefore, at least until the last decade, emphasis was put on "teaching to the test" rather than trying to develop various learning strategies and assessment modes.

Around the year 2000, the chemistry syllabus for chemistry majors was revised by a program committee, which placed great emphasis on laboratory work, context-based learning, and reading case studies and adapted scientific articles. These activities have become a mandatory part of the matriculation examinations (Barnea et al. 2010). Consequently, teaching and learning of higher-order thinking skills, such as inquiry skills, graphing skills, information analysis, modeling, and question posing, have become important elements of chemical education in Israel (Dori and Sasson 2008; Kaberman and Dori 2009a, b; Kipnis and Hofstein 2007).

Metacognition in Science Education

We present a review of metacognition applications in science education. We start with definitions and meaning of metacognition, and elaborate on knowledge of cognition and regulation of cognition, focusing on metacognition in science education in general and in chemistry education in particular.

In the next section, we discuss question posing and literacy aspects as a vital part of reading adapted scientific articles and case studies in science education.

Metacognition

Researchers define metacognition as awareness of and reflection upon one's own cognitive process, which can induce self-regulation and conscious coordination of learning tasks (Brown 1987; Flavell 1976, 1981).

Flavell (1979, 1981) described metacognition as knowledge about peoples' cognition, knowledge about cognitive tasks, knowledge about strategies that can be applied to the solution of different tasks, and skills for monitoring and regulating one's cognitive activities. Thus, metacognition refers to the awareness of one's own cognitive processes and the self-regulation and management of those processes in relation to the learning task. This includes conscious selection of strategies and matching strategy to task demands.

Main conditions for metacognition are (1) knowledge of thinking processes, (2) awareness of one's own processes, (3) the ability to control those processes (Flavell 1979), and (4) willingness to exercise that control (White 1998).

According to Koch (2001), metacognition is a hidden level of behavior that involves focusing on thinking about thinking and its relation to intellectual performance. Jacobs and Paris (1987) argued that researchers have generally circumvented the problem of defining metacognition by referring to two broad classes of metacognition: (a) knowledge that one has about a cognitive domain (e.g., reading, memory, or learning) and (b) strategies that regulate thinking (e.g., planning and monitoring). They also emphasized that automatic skills, no matter how sophisticated, do not necessarily imply metacognition on the part of the learner.

Metacognition and Self-regulated Learning

Self-regulated learning is the ability of students to understand and control their learning environments. To do so, students need to first set goals, and then select strategies that help achieve these goals, implement those strategies, and monitor progress towards these goals (Schunk and Zimmerman 1994). Self-regulated learning consists of three main components: cognition, metacognition, and motivation. Cognition relates to information encoding, memorizing, and recalling skills, while metacognition includes skills that enable learners to understand and monitor their cognitive processes, and motivation includes beliefs and attitudes that affect the use and development of cognitive and metacognitive skills (Schraw et al. 2006).

Self-regulated learning theory is rooted in cognitive psychology, dating back to the social-cognitive learning theory of Albert Bandura (1997), which has been

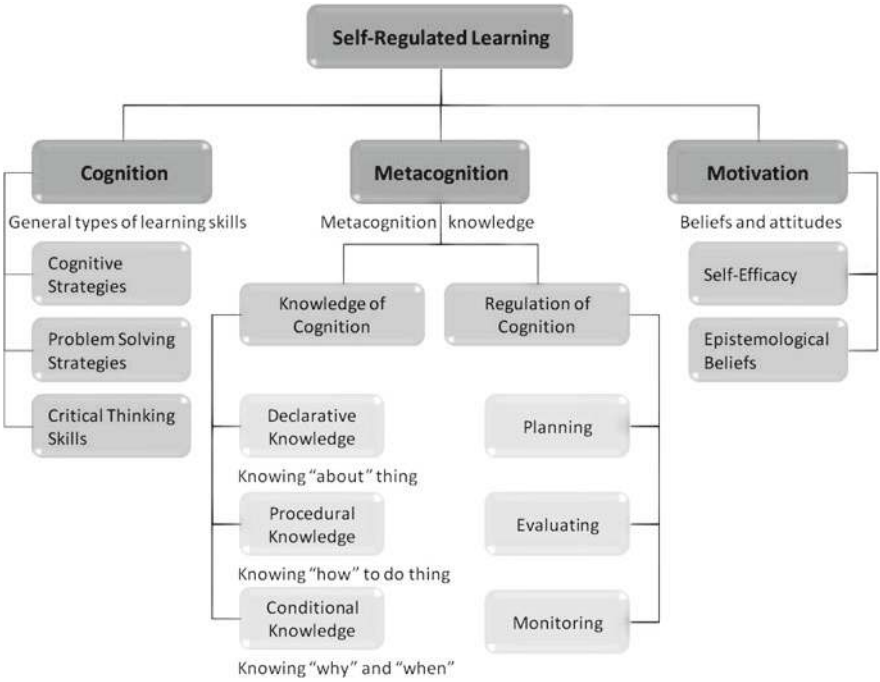

Fig. 8.1 Structure of self-regulated learning, integrated from Jacobs and Paris (1987); Schraw et al. (2006); and Schraw and Moshman (1995)

applied to many settings, including school learning. These applications have led to the development of self-regulated learning theory, which stipulates that learning is governed by interacting cognitive, metacognitive, and motivational components (Butler and Winne 1995; Zimmerman 2000). According to social-cognitive perspectives of self-regulated learning, individuals learn to become self-regulated by advancing through four levels of development: the observational level, the imitative level, the self-controlled level, and the self-regulated level (Schunk and Zimmerman 1994; Zimmerman 2000).

Referring to the metacognitive knowledge aspect of metacognition, Jacobs and Paris (1987) divided metacognition into two broad categories (as noted earlier): (a) self-appraisal of cognition – knowledge of cognition, and (b) self-management of thinking – regulation of cognition. These categories are in accord with the definitions of Schraw et al. (2006). Self-appraisal – knowledge of cognition – refers to the static assessment of what an individual knows about a given domain or task and includes three subcategories: declarative, procedural, and conditional knowledge. Self-management – regulation of cognition – refers to the dynamic aspects of translating knowledge into action and includes three types of processes: planning, evaluation, and monitoring. Figure 8.1 summarizes the structure of self-regulated learning, combining metacognition as one of its parts, along with cognition and motivation.

Schraw and Moshman (1995) defined declarative knowledge as "knowledge about oneself as a learner and about what factors influence one's performance" (p. 352) and stated that good learners appear to have more knowledge about their own memory and are more likely than poor learners to use what they know.

Jacobs and Paris (1987) referred to procedural knowledge as awareness of thinking processes, much of which is represented as heuristics and strategies. Conditional knowledge is the knowledge of knowing when and why to use declarative and procedural knowledge. It refers to awareness of conditions that influence learning, such as when and why to use a specific strategy.

Flavell et al. (2002) suggested dividing metacognition into metacognitive knowledge as one part and metacognitive monitoring and self-regulation as another. Kuhn suggested the term metastrategic knowledge as part of knowledge of cognition (Kuhn 1999, 2000). Knowledge of cognition concerns management of cognitive activity during problem solving and is expressed during problem solving and inquiry activities. Metacognitive monitoring and self-regulation resemble Schraw's regulation of cognition (Schraw 1998). He argued that metacognitive knowledge is multidimensional, domain-general in nature, and teachable. In summary, whereas cognitive strategies enable one to make progress in building knowledge, metacognitive strategies enable one to monitor and improve one's progress by evaluation of understanding and application of knowledge to new situations (Flavell 1979). Pintrich (2002) argued that unlike discipline- or domain-specific strategies, metacognitive strategies are applicable across most academic disciplines or subject-matter domains and can therefore be used across a large number of domains.

Metacognition and Meaningful Learning in Science Education

Traditional instruction modes are being criticized because they encourage passive rather than active learning and thus may lead to inert knowledge structure. Additionally, Kuhn (1989) argued that students have a great deal of difficulty engaging in scientific reasoning because they fail to understand how theories work.

Developing students' metacognitive skills, in order for them to be able to study any desirable knowledge, has become essential in view of the exponential increase in scientific and technological knowledge, since it is difficult to predict what knowledge will be essential for the future (Georghiades 2004).

Teaching metacognitive skills calls for integrating special instruction modes into students' learning. Schraw and Moshman (1995) proposed that instructional programs should include, in addition to subject matter, the following instructional components: (a) a rationale for the importance of metacognitive theories, (b) examples of informal and formal metacognitive theories, and (c) ways to construct metacognitive theories. An example of integration and implementation of these components is introduced in the learning unit *Taste of Chemistry* (Herscovitz et al. 2007a), written in Hebrew for 11th grade chemistry majors. In this unit, a specially designed

metacognitive tool was constructed based on the four chemistry understanding levels (Kaberman and Dori 2009a). The tool guides the students how to monitor the use of macroscopic, microscopic, symbol, and process chemistry understanding levels as they reason about their responses to assignments (Avargil et al. 2011). The four chemistry understanding levels serve as scaffolds for constructing chemical knowledge and thinking (Barak and Dori 2005; Dori et al. 2005; Dori and Hameiri 2003; Dori and Sasson 2008).

Becoming aware of the thought processes and knowledge in one's mind can be helpful for solving problems and thinking in a metacognitive way. It can also serve as goals for a student who is willing to self-regulate and learn from others (Paris and Oka 1986). As for the question of when individuals are first "ready" to engage in metacognitive theorizing, many researchers believe that metacognitive awareness and experience should be developed hand in hand, starting with basic skills instruction (Flavell 1976, 1979, 1987; Montgomery 1992; Schraw and Moshman 1995).

White (1998) has indicated that science educators have worked more intensively on metacognition in comparison to educators of other domains. A possible reason for this is the complexity of science, which is well-suited to the inquiry and reflective nature of metacognition.

Paris and Winograd (1990) have argued that students' learning can be enhanced by becoming aware of their own thinking as they read, write, and solve problems. They noted that teachers should promote this awareness by informing their students about effective problem-solving strategies and discussing cognitive and motivational characteristics of thinking. Students who are not used to thinking in a metacognitive mode sometimes resist having to do so, especially if they have been passive learners for many years. Students need scaffolding instruction and ongoing support during their initial steps of thinking in a metacognitive mode. Later, as they become more proficient at self-regulation, this support can be gradually withdrawn (Hartman 1994).

Simons and Klein (2007) examined how scaffolds influence inquiry and performance in a problem-based learning environment. They concluded that use of scaffolds plays an important role in enhancing students' performance within problem-based learning (PBL). While investigating interventions that enhance students' metacognition, Thomas and McRobbie (2001) have found that if students' metacognition was improved, then it was possible to improve their learning outcomes.

Students who experience an inquiry activity realize that they become empowered by gaining proficiency in acquiring knowledge in any content domain and by being able to carry this inquiry as well as to initiate, manage, and execute on their own new experiments (Kuhn et al. 2000).

Some researchers found that science laboratory is a suitable experience for creating an environment that promotes metacognitive abilities. Kipnis and Hofstein (2007) have found that the inquiry laboratory activity provides students with opportunities to practice their metacognition throughout the different stages of inquiry-type experiments. The utilization of this opportunity depends on many factors, such as the teacher's behavior, the inquiry activity, and the laboratory environment. Kaberman and Dori (2009a) have found that students who used metacognitive strategies, such as self-monitoring, self-questioning, and self-assessment in a

case-based computerized laboratory (CCL) environment were academically more successful than students who did not use these strategies.

Several researchers studied strategies for measuring metacognition knowledge. Anderson et al. (2008) conducted a large-scale study that investigated the elusive nature and character of high school students' metacognition across formal and informal science learning contexts. They reviewed and conceptualized several methods employed in qualitative-interpretive studies of metacognition. In their conclusions, they pointed out that the use of group interaction and engagement and the collective group reflection of learning experiences is a powerful mechanism that reveals metacognition in ways that solitary experiences cannot. In another study, Thomas et al. (2008) developed an empirical self-report instrument for providing a measure of students' metacognition, self-efficacy, and constructivist science learning processes. The Self-Efficacy and Metacognition Learning Inventory – Science (SEMLI-S) questionnaire consists of 30 items which are divided into five sub-scales: (1) constructivist connectivity; (2) monitoring, evaluation & planning; (3) science learning self-efficacy; (4) learning risks awareness; and (5) control of concentration. The items can be used for analyzing and focusing on any or all of its dimensions, or for assigning scores to individuals, that enable comparison between them in relation to their metacognitive science learning orientations.

Teaching and Learning Science in a Case-Based Environment

Starting at business and medical schools, the case method has become a model for effective learning. The case-based environment refers to integrating case studies into teaching and learning. Case studies, also known as case narratives, are (usually real) stories with a message, which are relevant to the students' daily lives (Dori and Herscovitz 2005). Cases can contain scientific aspects, mostly adapted from scientific articles, and can involve chemical, environmental, emotional, ethical, or political issues. While reading the case study, students are required to solve various tasks, including posing questions related to the case, analyzing data presented in tables and graphs, and arguing critically about topics arising from the case (Dori and Herscovitz 1999).

Our prior experiences of case-based teaching and learning in school science classroom environments (Dori and Herscovitz 1999, 2005; Dori and Tal 2000; Dori et al. 2003) as well as in the laboratory environment (Dori et al. 2005; Dori and Sasson 2008; Kaberman and Dori 2009a, b) have shown that the case study method is effective for elevating the level of students' higher-order thinking skills, such as chemical understanding, inquiry, graphing, and question posing, as well as enhancing their critical thinking and motivation to learn. Based on these experiences, we found that in the case-based environment students are encouraged to discuss their own knowledge and to monitor, evaluate, and control their knowledge construction and cognitive processes.

Question Posing as a Part of Chemical Education Literacy

The main purpose of high school education is to foster the development of educated citizens who have acquired learning and thinking skills as well as a significant body of knowledge. Chemical literacy includes understanding the particulate nature of matter, knowledge of chemical interactions between substances to create new ones, and the ability to use laws and theories to explain chemical phenomena. The uniqueness of chemistry education is the need to internalize the tight relationships between the macroscopic and microscopic worlds in order to understand situations and phenomena that have chemical foundations (Schwartz 2006).

Young children are inherently curious, frequently asking a stream of questions. However, many elementary school students are already at a stage in which they have stopped asking questions and they do not articulate a desire to discover, debate, or challenge (Becker 2000). Dillon (1988) found that when students did ask questions, the questions were seldom designed for increasing their personal knowledge or understanding. Rather, they were procedural, informational, and focused on the content covered in the next test.

Emphasis on students' questions conveys the message that inquiry is a natural component in a variety of science disciplines and that questions need to be constantly raised (Woodward 1992). The value of student questioning has been emphasized in the National Science Education Standards, which stated that "inquiry into authentic questions generated from student experiences is the central strategy for teaching science" (NRC 1996, p. 31). It is not generally possible to define the quality of students' posed questions, but it is possible and desirable to provide teachers with research-based sets of working criteria for guiding their students how to pose complex questions (Arzi and White 1986). For students to be active learners and independent thinkers, they must generate questions that shape, focus, and guide their thinking (Singer 1978).

Dori and Herscovitz (1999) who found that the Air Quality module, in which students were taught how to generate "good and complex" questions, brought about a significant increase in students' question posing capability in the aspects of number of questions, their orientation, and their complexity.

The Two Studies: Overall View

Reading adapted scientific articles is a vital part of communicating scientific knowledge to high school students, our future citizens. A major goal of science teaching is therefore to prepare an independent life-long learner who can read and understand new texts independently. Researchers (Duffy et al. 1987; Jacobs and Paris 1987; Yarden 2009) believe that reading is an active process which demands constructing new knowledge and linking it to prior knowledge. Scientific texts, which differ from other texts in their goals, structure, and cognitive demands, call for metacognitive strategies and higher-order thinking skills.

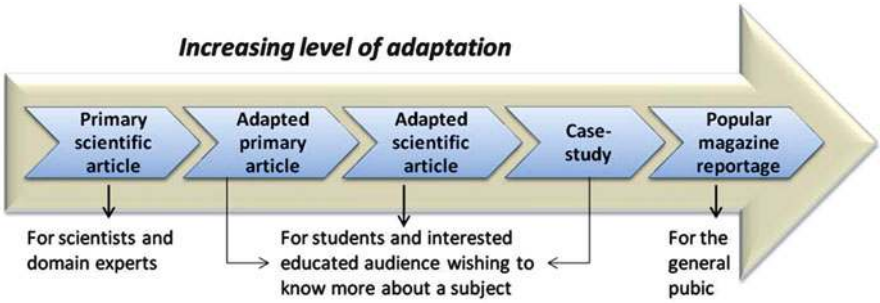

Fig. 8.2 Differentiation levels of scientific article adaptation

The goal of the two studies, which we describe in what follows, was to investigate the effect of exposing high school chemistry students to metacognitive tools while reading case studies (study I) and adapted chemical articles (study II) on their ability to pose questions.

We distinguish between case studies and adapted scientific articles by the degree of adaptation or modification that the original or primary scientific article has gone through in order to improve students' understanding. Considering the full spectrum of adaptation, we define a scale for differentiation between levels of scientific article adaptation as presented in Fig. 8.2.

The primary scientific article is written by scientists for scientists, for communication among scientists. It includes evidence to support conclusions (mainly in the Methods and Results sections) and constructed in a canonical manner (Abstract, Introduction, Methods, Results, Discussion).

The adapted primary scientific article also includes evidence to support conclusions and is written in a canonical manner. However, unlike the original article, it is usually written by science educators and scientists for students and not for their own community, i.e., scientists (Falk and Yarden 2009; Yarden 2009). The adapted scientific article, as defined here, is usually written by science educators and scientists, using an expository genre. It is not structured in a canonical manner, and it contains mainly facts with less evidence (in comparison to the primary articles) to support the conclusions. As mentioned earlier, we define adapted scientific articles as articles which are based on scientific articles that are mostly from secondary sources.

The case studies are shorter than adapted scientific articles and are written in a manner that is more relevant to the students' daily lives (Dori and Herscovitz 1999, 2005). They can involve emotions, environmental, ethical, or political issues. The chemistry-domain aspects are introduced in a plain manner, and complex chemical information is limited.

The primary and adapted scientific articles differ from a popular magazine reportage as the latter is written in a non-scientific language and contains less scientific subject matter.

In order to better differentiate between an adapted scientific article and a case study, we define a set of four categories to analyze the complexity level of the adapted scientific article following our previous studies (Dori and Herscovitz 2005).

Table 8.1 Categories and scores for classifying the adaptation level of a scientific article

Category	Scoring scheme
Article length	1. Short texts contain up to 400 words 2. Long texts contain more than 400 words
Article type	1. Easy to read ("story like") and focuses on basic chemical information 2. Integrates complex scientific information
Student's tasks	1. Limited number of questions and thinking skills involved. The expected response is short and chemistry oriented 2. Various questions which require short chemistry oriented responses, or a few questions which involve various thinking skills and chemical aspects 3. Large variety of questions which involve various thinking skills and chemical aspects
Interdisciplinarity level	1. Only the chemistry domain is involved 2. Two domains are involved, limited integration, mainly chemical aspects 3. Two or more domains are involved, deep and complex integration

Our aim in creating the rubric for determining the complexity level of an article stemmed from a need that came up in our two studies, which are described in detail in the sequel. In the first study, we used case studies, and in the second one – adapted scientific articles. The categories and the assessment scheme we used to identify the adaptation level of adapted articles are presented in Table 8.1. The categories for comparing between the two types of articles included article length, article type, student's tasks, and interdisciplinarity level. Interdisciplinarity level is one of the criteria since most scientific articles involve aspects from more than one scientific domain and might also discuss societal, industrial, and ethical aspects.

Each article was scored between 3 and 10. An article was defined as a case study (which students read in Study I) if its complexity level scores ranged between 3 and 6. If the article scored higher, between 7 and 10, we referred to it as an adapted (secondary) scientific article (which students read in Study II).

The description of each of the following studies includes research objectives, the metacognitive tool, research participants and setting**,** methodology, and findings.

Study I – Metacognition and Question posing Skill Enhancement in the Chemistry Case-Based Computerized Laboratory Learning Environment

The study is concerned with question posing and its relation to metacognitive knowledge. We developed a case-based computerized laboratory (CCL) learning unit designed for 12th grade honors chemistry students (Dori et al. 2004).

The CCL environment exposes the students to reading case studies and to metacognitive knowledge of question posing strategies, supported by a metacognitive tool – a question classification taxonomy – which we describe below. The CCL unit calls for reading case studies, posing questions, conducting computerized inquiry laboratory activities, and engaging in molecular modeling. The study described here is part of a larger study which examined the effect of the CCL learning environment on fostering students' higher-order thinking skills. The thinking skills we investigated included question posing, modeling, inquiry, graphing skills, and transfer (Dori and Sasson 2008; Dori et al. 2004; Kaberman and Dori 2009a; Sasson and Dori 2006).

One central component in the CCL environment was the case studies, followed by question posing tasks. Each of the five laboratory topics in the learning unit, e.g., energy or acid–base, began with a case study introducing a daily life chemical phenomenon related to the inquiry laboratory that the students were about to experience. The last part of each topic included another case study, which dealt with a different aspect of the subject matter under study.

Research Objective

The objective of the research was to examine how an integrated metacognitive tool affects students' skill to pose complex questions and to analyze them according to a specially designed taxonomy.

The Metacognitive Tool

The metacognitive tool for question posing, which we designed for use by students, included question classification taxonomy. The taxonomy enabled chemistry students to assess the quality of the questions they had posed. The assessment was based on characterizing the questions according to a three-component taxonomy: (a) content – the question should not only focus on the phenomenon described in the text. It should involve such aspects as potential hazards or endangerments, or their possible solutions; (b) Thinking level – the question requires a response at a thinking level higher than knowledge or understanding; and (c) chemistry understanding levels – the question calls for a response that requires the invocation of at least two out of the four chemistry understanding levels – symbolic, macroscopic, microscopic, and process.

This taxonomy provided different aspects of examining the complexity level of the questions posed in relation to a chemical text and defined what constitutes a "complex" question in this context.

Research Participants and Setting

The research participants were 793 Israeli high school 12th grade chemistry students, of whom 45% were males and 55% females. They were taught by 28 teachers. As part of their training program, all the chemistry teachers were exposed to the metacognitive tool. The teachers participated in a week-long CCL summer training program at the Technion, where they were directed to instruct the program with emphasis on applying the case-based method and the question posing metacognitive strategy.

In their classrooms, after reading the first case study, the teachers worked on improving their students' question posing skill, asking the students to pose as many questions as they could. These had to be questions related to the case study, to which the students could not find a direct answer from the text. After creating a list of 10–15 student-posed questions, the students' next task was to sort the questions by categories, using only their judgment, without any further explanation from the teacher. In each class, the different questions were sorted by a host of parameters and categories which the students had devised. These categories served as a platform for the teachers to expose the students to the metacognitive tool for creating a question classification taxonomy.

Having presented the metacognitive tool, the questions posed by the students were written on the board and sorted again by the students and the teacher together. Each question was analyzed for the different aspects of the taxonomy in a class discussion, and a joint decision was made regarding whether one or more of the aspects were missing from it and in what aspects the question could be considered as complex.

As the academic year progressed, while learning the CCL unit, students read more case studies – seven in total. Supported by the metacognitive tool, they posed questions related to these case studies. Our assumption was that repeating the same skill in different scientific contexts potentially helps the students to formulate better questions.

Methodology

Six students were interviewed regarding their question posing skill in order to examine the metacognitive learning processes occurring in the CCL environment. Students were also evaluated for their question posing skill by pre- and post-questionnaires.

In order to present a broad view of the metacognitive knowledge of the students in our study, both qualitative and quantitative research tools were used (Denzin and Lincoln 2000; Johnson and Onwuegbuzie 2004).

Students' Semi-structured Interviews

The six students we interviewed, three males and three females, represented students of high, intermediate, and low academic levels. The objective of the interviews was

A chocolate diet?

Until recently, chocolate was considered a fattening and teeth damaging bar. Nowadays, the reputation of chocolate is changing. Based on a considerable number of researches, scientists claim that eating chocolate contributes to decreasing the risks of heart and blood vessel diseases. Researchers found that cocoa powder, produced from cocoa beans, one of the chocolate's components, contains a variety of antioxidants called flavonoids. Those antioxidant components partly prevent oxidation reactions of fats in the blood. Oxidized fats may cause the development of atherosclerosis illness, a main death cause in the Western world. People who suffer from atherosclerosis have accumulation of oxidized fats, i.e., cholesterol on the side walls of their arteries.

In one research, volunteers were given different amounts of bitter chocolate. The findings showed that the higher amounts of chocolate volunteers consumed, the higher concentration of a flavonoid called epicatechin was found in their blood plasma, and the lowest oxidation damage occurred to their blood fats.

Nevertheless, fruit and vegetables, which also contain antioxidants, contain in addition other nutritional components as dietary fibers, vitamin C and beta carotene. In light of this information, is it wise to recommend adding chocolate to our daily nutrition in order to improve our heart's condition?

Fig. 8.3 A case study used in the interviews

to understand the metacognitive processes these students underwent while developing their question posing skill and practicing it with the question taxonomy. At the beginning of the interview, each of the students read a case study, following which, one of the researchers asked him/her to pose questions about that case study.

Figure 8.3 describes an example of a case study which was presented in the interview.

During the interview, these students analyzed their questions using the think-aloud method, explaining why they had posed those particular questions and how they took the different aspects of the taxonomy into consideration.

The students were interviewed at an early stage, before completing the CCL learning unit, while they were still practicing the questions taxonomy. Because of the rather early stage of the interview, the interviewer intervened, clarified what she meant, and sometimes had to remind parts of the taxonomy to the interviewees. The interviewer used the taxonomy as a metacognitive tool for question posing, encouraging the students to improve the questions they had posed in the beginning of the interview.

Case-Based Questionnaires

To assess the question posing skill, we used pre- and post-questionnaires, following the idea that the assessment tool should match the teaching and learning approach. Each of the questionnaires included a case study related to a chemical story and a variety of assignments for investigating various thinking skills. Students were asked to pose two questions to which they did not find a direct answer in the case study.

Table 8.2 Rubric for assessing students' question posing skill

Score	Content	Thinking level	Number of chemistry understanding levels[a]
0	The question is irrelevant and not related to the case study	The response to the question is fully described in the case study	The question is not related to any chemical aspect
1	The question is directly related to a phenomenon that appears in the text	The question requires a response at the knowledge and understanding level	One chemistry understanding level is required
2	The question deals with hazards and possible solutions that could be traced from the text	The question requires a response at a thinking level higher than knowledge and understanding, for example: • Information analysis and application, the ability to identify problems and make conclusions; • Inquiry questions, assessment, critical thinking, position taking	Two chemistry understanding levels are required
3	–	–	Three chemistry understanding levels are required

[a]Macroscopic, microscopic, symbol, and process

The students' questions were analyzed according to a rubric we had designed based on the question taxonomy – the metacognitive tool (see Table 8.2).

This taxonomy helped us determine the complexity of each question a student posed based on the anticipated response to that question. Two aspects of this taxonomy – the question content and its required response's thinking level – had been defined and evaluated in previous work (Dori and Herscovitz 1999, 2005).

The third aspect – chemistry understanding levels required for responding – was presented and utilized in this study for the first time (Kaberman and Dori 2009a).

Each question is scored separately for its content, thinking level, and chemistry understanding level. The total question score is the sum of these three aspect scores.

When calculating students' scores in the question posing skill, we summed the scores for the two questions the student had posed and normalized it to a 0–100 scale.

Findings

We present the results of interviews of two students out of six interviewees and of the case-based questionnaires that the 793 chemistry students responded to throughout the research.

Student O. (a low academic level student)
Posed question –The cognitive process
Given the same amount of chocolate and fruit, which contains more antioxidants?
Think-aloud – The metacognitive process of formulating the question
I picked a particular fact from the text.
Researcher interpretation
Explanation: Focusing on specific sentences / changing words order in order to turn them into questions.
Metacognitive level: Low

Student A. (a high-academic level student)
Posed question –The cognitive process
How does the amount of dark chocolate affect the damage of blood lipids oxidation and the chance of having atherosclerosis?
Think-aloud – The metacognitive process of formulating the question
The third paragraph discussed a scientific research and my question summarized that paragraph. I read [the case study] for the first time, and divided it to paragraphs by topics. In the first paragraph there was nothing to ask because it was only an introduction, a teaser... The second question dealt with the third paragraph. I extracted the question from the paragraph.
Researcher interpretation
Explanation: First reading the whole article, dividing it to paragraphs, and then extracting the essence of each paragraph for posing questions.
Metacognitive level: High

Fig. 8.4 Cognitive and metacognitive processes while formulating a question

Qualitative Analysis: Students' Interviews

Analysis of the think-aloud scripts of the six students as they progressed in posing questions during their interviews revealed three main metacognitive strategies:

(a) Analyzing a self-posed question by thinking level,
(b) Analyzing a self-posed question by chemistry understanding level, and
(c) Reflecting on the process of formulating a question.

Figures 8.4 and 8.5, as well as Tables 8.3 and 8.4, present the three main metacognitive strategies of one low-academic-level student and one high-academic-level student (of the six students interviewed) based on their interviews conducted by one of the researchers.

Figures 8.4 and 8.5 present examples of the questions posed by the interviewees, demonstrating the cognitive processes they went through. For each question, a think-aloud quotation, representing the student's corresponding metacognitive process, is provided. The metacognitive process in Fig. 8.4 reflects on the way the students formulated the question, whereas in Fig. 8.5, the metacognitive process relates to the way the students analyzed their self-posed question's thinking level.

Interpreting the students' quotations, we found that questions focusing on specific sentences in the text or changing word order yielded low-level knowledge-type questions and the strategies students elicited characterize low-level metacognitive processes. Summary questions posed by the interviewees required both knowledge and understanding in order for them to be answered correctly. We classified the corresponding metacognitive strategy level as intermediate. Finally, students whom we classified as having high metacognitive level developed strategies for identifying the central theme of the case study or for extracting the essence of the text.

Student O. (a low-academic-level student)
Posed question – The cognitive process
What kind of antioxidants do fruit and vegetables contain in comparison to chocolate?
Think - aloud – The metacognitive process of analyzing the self-posed questions
It is hard to pose questions… you need to pose the right questions… not yes or no questions because these are too simple, you don't reach other layers
Researcher interpretation
Explanation:The student realizes the need to reach deeper layers.
Question's thinking level - Knowledge
Metacognitive level – Low.

Student A. (a high-academic-level student)
Posed question – The cognitive process
How does a lipid oxidation reaction occur?
Think-aloud – The metacognitive process of analyzing the self-posed questions
In order to answer that question you need to open an encyclopedia or find other information resources.
[I try to ask] *questions to which the answer requires a short or a long explanation-there has to be an explanation.*
Researcher interpretation
The student realizes the need to pose questions that require detailed justifications. Question's thinking level – Knowledge and understanding
Metacognitive level – Intermediate.

Fig. 8.5 Cognitive and metacognitive processes while analyzing a self-posed question by thinking level

Table 8.3 Development of the metacognitive processes while analyzing a self-posed question by chemistry understanding level – **Student O. (**a low-academic-level student)

Stage	Beginning of interview	Middle of interview
Posed question	*Given the same amount of chocolate and fruit, which contains more antioxidants?*	*Do antioxidants in fruit and chocolate act similarly against atherosclerosis?*
Interviewer probing	Why was it difficult for you to compose questions?	What criteria are needed to characterize a question as simple? How can you make your question more complex?
Think aloud – The metacognitive process of analyzing the self-posed questions	*I was looking for the correct question. My first question was a simple one.*	*The answer to the question has to be relevant to everyday life, include expressions of how the phenomenon appears in the microscopic level, and if you can see it with your eyes…I don't exactly know…*
Researcher interpretation: complexity	Student O. recognized the need for making the question more complex, but could not apply it in the analysis of her questions	
Researcher interpretation: chemistry understanding level	Micro	Micro and process
Researcher interpretation: metacognitive level	Low	Intermediate

Table 8.4 Development of the metacognitive processes while analyzing a self-posed question by chemistry understanding level – Student A. (a high-academic-level student)

Stage	End of interview
Interviewer probing	Can you ask another question while thinking what levels of chemistry understanding are required to answer it?
Posed question	*How does the amount of dark chocolate being eaten, affect the blood fats oxidation damage, and the risk of having atherosclerosis?*
Think aloud – The metacognitive process of analyzing the self-posed questions	*You need to have people, feed them with dark chocolate and trace the development of atherosclerosis – macro level.*
	Process level – flavonoids that reduce the oxidation damage.
	Symbol level – we need to use chemical symbols in order to describe the process.
	Micro level – what happens in the blood…it's a little difficult to think about the difference between micro and process levels. The question requires an answer in four levels and is not a yes or no question.
Researcher interpretation: Explanation	The student was able to pose a complex question, and while analyzing the chemistry understanding levels, she identified all the four levels
Researcher interpretation: chemistry understanding level	Micro, macro, symbol, and process
Researcher interpretation: metacognitive level	High

Students understanding was manifested by the complex questions they posed, which required higher-order thinking responses.

The students were able to explain the kinds of questions that were considered as simple, with no complex characteristics, e.g., yes or no questions, questions that called for a one-word answer, or questions to which the answer could be found in the text. However, student A., for example, chose to pose types of questions which required responses with detailed justifications or critical thinking. Toward the end of the interview, most of the interviewed students formulated inquiry questions, which they (and we, the authors) considered as ones requiring higher-order thinking. The metacognitive process the students expressed was in line with the amount of higher-order thinking required to answer the posed question.

Tables 8.3 and 8.4 demonstrate how students developed their questions as well as their metacognitive processes during the interview with respect to chemistry understanding levels.

Quantitative Analysis of the Questionnaires

The students' question posing skill was analyzed in both the pre- and the post-questionnaires using the rubric presented in Table 8.2 (Kaberman and Dori 2009a). The average post-scores of the question posing skill of students were higher

Table 8.5 Distribution of questions posed sorted by the main combinations of chemistry understanding levels

Percentage of questions	Macro, micro and process	Micro and process	Macro and process	Macro and micro	Process	Macro
Pre (N = 1,247)	9	7	10	4	15	42
Post (N =1,748)	15	15	21	7	10	33

in comparison to their pre-scores. The net gain (post-scores minus pre-scores) of the students in the question posing skill was analyzed, and the effect size of the net gain score was 0.65 ($p<0.0001$). The number of questions students posed in the post-questionnaire and their complexity were both significantly higher than in the pre-questionnaire. The number of students who posed questions that required higher-order thinking skills in the post-questionnaire was double that number in the pre-questionnaire (29% vs. 14%).

The Chemistry Understanding Aspect

When examining the questions students posed by the chemistry understanding levels that are required for answering them, we focused not only on the number of chemistry understanding levels being used but also on the different and most common combinations of those levels. Table 8.5 presents the analysis of all the questions that were posed by the 793 students and their distribution according to the different combinations of chemistry understanding levels.

As Table 8.5 indicates, more questions were posed in the post-questionnaire than in the pre-questionnaire. Many questions posed in the pre-questionnaire (57%) called for a response that required the invocation of one chemistry understanding level only – the macroscopic or the process level. In the post-questionnaire, less questions (43%) requiring response in only one chemistry understanding level were asked, and more of these questions called for invoking the microscopic level. There was an increase in the percentage of questions calling for response that requires the application of three chemistry understanding levels – macroscopic, microscopic, and process (from 9% to 15%). Other questions required response that had to use different chemistry understanding level combinations, but since there were only few questions dealing with symbols, we present only the main combinations that emerged from the questions students had posed.

Study II – A Metacognitive Tool for Assessing Chemistry Students' Reading Strategies and Question posing Skill While Reading an Adapted Scientific Article

The incorporation of reading tasks into courses for students who major in chemistry is aimed at making the topics more relevant and interesting for the students. Understanding adapted chemical articles in chemistry requires the application of at

least a subset of the four chemistry understanding levels – symbolic, macroscopic, microscopic, and process.

As in Study I, we used the chemistry understanding levels in this study for two purposes: (1) as part of the metacognitive tool introduced to the students to create a scaffold for posing questions and (2) for assessing the quality of students' responses.

Study II is part of a larger study aimed at investigating the way Israeli high school students comprehend the adapted scientific articles they read. In the large study, we investigated four aspects: identifying the main issue in the article, chemistry comprehension of the article at both textual and visual representations modes, question posing, and transfer skills. Here we focus on the students' question posing skill.

Research Objectives

The research objectives were to (a) identify the strategies students used while reading the adapted articles – *knowledge of cognition*, and (b) investigate the influence of integrating a specially designed metacognitive tool on students' question posing ability. For the second question, we investigated the complexity level of the questions posed by the students – *cognition*, as well as their reflections on the process of asking these questions – *regulation of cognition*.

Research Participants and Setting

The research participants included about 400 11th and 12th grade chemistry majors from a variety of schools in the center and the northern parts of Israel. The students were divided into one experimental and two comparison groups (I and II) based on the number of adapted scientific articles they read and the extent of their usage of the metacognitive tool.

Comparison group I served for assessing the effect of using the metacognitive tool, while comparison group II served for assessing the effect of the time elapsed between reading the first and the fifth (last) article.

The research groups' description is presented in Table 8.6.

All research groups responded to the same tasks following the reading of the adapted scientific article and responded to the same pre–post questionnaires. Reading an adapted scientific article, which was 500–600 words long, and answering the questions that followed it took one session (45 min). There was a gap of 3–4 weeks between reading two successive articles. The experimental group started using the metacognitive tool, described below, after reading the second adapted article. The titles of the five adapted scientific articles are: (a) Walking on the Ceiling with Geckos, (b) Diamond Forever, (c) The Baghdad Vessel Mystery, (d) Strongest but Gentle Acid, and (e) Oceans Becoming More Acidic.

Table 8.6 Research groups and activities performed by each group

Research group	Reading articles and answering followed questionnaires	Using the metacognitive tool
Experimental	All five articles	Yes
Comparison I	All five articles	No
Comparison II	Only the first and last article	No

Posing complex questions is one indication for a better understanding of an article. Three characteristics indicate questions' quality:

(a) ***The thinking level required for answering the question*** *(Dori & Herscovitz, 1999; Kaberman & Dori, 2009a; Zoller, 1993).*

- *Low order thinking level – answering the question requires knowledge that can be found in the article or in another source;*
- *Higher order thinking level – answering the question requires knowledge that cannot be found in the article. The question calls for implementation, information analysis, inquiry, critical thinking or argumentation.*

(b) ***Number of chemistry understanding levels required for answering the question*** *(Kaberman & Dori, 2009b). A complex question related to chemistry requires at least two chemistry understanding levels in order to respond to it adequately.*

(c) ***Contribution of information needed for better understanding of the article.***

A question is considered complex when the answer requires higher order thinking, at least two chemistry understanding levels, and additional valuable information for comprehending the article.

Use the following table to monitor the questions you posed in order to determine their complexity:

Question	*Thinking level*	*Chemistry understanding levels*	*Contribution to the article*
1			
2			

Fig. 8.6 The set of guidelines for posing questions, which was part of the metacognitive tool

The Metacognitive Tool

The metacognitive tool we developed is aimed at improving meaningful comprehension of adapted scientific articles reading. The tool includes four sets of guidelines for monitoring step-by-step comprehension: (1) identifying the main issue in the article; (2) chemistry comprehension of the article based on identifying the chemistry understanding levels required for answering the questions followed the article; (3) posing questions, which is the focus of this chapter; and (4) transfer skill.

The set of guidelines for posing questions, which was part of the metacognitive tool, is presented in Fig. 8.6. The metacognitive aspect of this tool is manifested primarily in the requirement of the user to reflect on the question posed in order to identify the thinking skill and the chemistry understanding levels required for answering the questions.

Read the following article and then answer the questions, assuming you are to be tested for understanding the article.

1) *What method do you usually use for reading and understanding the article? Explain your favorite method.*
2) *Would you use a different method for reading and understanding an article in a history book as compared to a science book? If so, explain the difference.*
3) *Do you often construct your own charts, outlines, or diagram as you read a new article? If so, which of those "organizational tools" seems to work best for you?*
4) *Are you using the same method each time you read a text or trying to use various methods? Explain.*
5) *While reading a new article, do you ask yourself questions? If so, give an example for one such question.*
6)

a) In the pre-questionnaire for all research groups – *Are you interested in having guiding instructions for meaningful reading of scientific articles? Please explain why.*
b) In the post-questionnaire for the experimental group – *Had the guiding instructions for meaningful reading of scientific articles you used assisted you to better understand the articles? Explain how.*
c) In the post-questionnaire for the comparison groups – *If you had been given guiding instructions for reading the articles, do you think they could have assisted you better understand the articles? Explain why.*

Fig. 8.7 Wandersee's adapted questionnaire for examining students' reading strategies

Methodology

In order to examine the metacognitive knowledge that chemistry high school students applied while reading an article, all the participants in the research responded to two types of pre- and post-questionnaires. One questionnaire, aimed at identifying students' reading strategies, was adapted from Wandersee's questionnaire – *Ways Students Read Texts* (1988). The other questionnaire – the adapted article questionnaire – was aimed at examining students' cognitive and metacognitive knowledge while reading an adapted article.

Wandersee's Adapted Questionnaire

The questionnaire included six questions; five were identical in pre–post questionnaires and were identical to the ones in the original tool (Wandersee 1988). The last question was formulated for this study and was slightly different in the post-questionnaire than in the pre-questionnaire. The questionnaire is presented in Fig. 8.7.

When conducting content analysis of students' responses to question 1 in Wandersee's adapted questionnaire, we identified three strategies for reading and understanding adapted articles:

- Skimming (low strategy, 1 point) – Searching answers to the following questions by repeated rereading and/or reading aloud

Table 8.7 Categories and examples of students' self-questioning while reading

Category	Score	Examples
Understanding the subject	1	*What is the article about?*
Looking for the meaning	2	*What is the main subject and do I understand it?*
Connecting information to the reader	3	*What new information did I gain from the article that I didn't know before?*
Connecting to prior knowledge	4	*How is it related to what we learned in school?*

- Looking for meaning (intermediate strategy, 2 points) – Looking at the title, using organization tools (outlines, diagrams, highlight of a basic term or a key word)
- Contextual understanding (high strategy, 3 points) – Connecting to prior knowledge

Analyzing students' responses to question 5 in Wandersee's adapted questionnaire, which calls for examples of students' self-posed questions while reading the article, we found four categories of self-posed questions while reading the article. The categories, examples of self-posed questions, and their scores of Question 5 in Wandersee's questionnaire are demonstrated in Table 8.7.

The Adapted Article Questionnaire

The adapted article questionnaire was designed for identifying students' cognitive and metacognitive knowledge and contained article reading which included 400–600 words and a variety of the following tasks: (a) identifying the main subject of the article, (b) understanding chemistry at as many chemistry understanding levels as possible and expressing it both textually and graphically, (c) posing complex and deep questions, (d) reflect on the choice students made by asking those questions, and (e) responding to a question that requires transfer to a context of a different subject matter. In this chapter we focus on items (c) and (d).

The (c) and (d) tasks were phrased as follows: "Compose two additional questions which you would like to ask the expert researchers regarding issues that were not sufficiently detailed in the paper. Explain why you chose these two questions." We analyzed the questions students had posed according to three categories: the thinking levels; the chemistry understanding levels required in order to respond to the posed question; and the added value of the answer to the question to the information the student gained from reading the article, which we abbreviate as *contribution*. The first two categories are based on previous studies (Dori and Herscovitz 1999; Kaberman and Dori 2009a, b), while the third category is used for the first time in this study. In each of the three categories, the highest score was 2 and the total score for each posed question was 6 (which was later normalized).

In order to analyze students' reflections on posing their questions, we used five categories that classify these reflections by their quality and thinking level (Bloom 1956; Resnick 1987). The five categories, their thinking level, and examples of students' reflections as well as their scores of Question d in the adapted article questionnaire are presented in Table 8.8.

Table 8.8 Criteria for analyzing students' reflections on the process of posing questions while reading the adapted article

Category	Thinking level	Example	Score
No justification		*"Just so", "because…"*	0
Asking for more information	Knowledge	*Questions which contribute to text understanding and to making it more interesting*	1
Wondering about application	Application	*Wondering about the usefulness or efficiency of the innovation or application*	2
Inquiry related to the chemistry in the text	Analysis	*Asking if the same result can be achieved using another metal or substance*	3
Value judgment	Critical Thinking	*Investigating the value of developing the material for applications (e.g., wall climbing)*	4

Findings

Knowledge of Cognition

Based on experimental students' responses to *Wandersee's adapted questionnaire*, we found that the percentage of these students claiming no use of reading strategies decreased in the post-questionnaire, while the percentage of the students claiming they ask questions that require connection to prior knowledge (defined as high metacognition level) increased.

Based on students' responses to question 5 in Wandersee's questionnaire, half of the students in all three groups noted that they had asked themselves questions while reading the article, but about half of these students asked only low level questions, which merely assisted in understanding the subject. Only a few students wrote they had asked questions connected to prior knowledge, which are high-level questions.

The change that students went through during the research period reveals a significant improvement in the quality of questions experimental students asked themselves while reading the adapted articles. The experimental group improved their questions significantly as they moved from low- to intermediate- and high-level questions in comparison to the other groups ($\chi_8^2 = 15.5, p < 0.05$). Interestingly, comparison group II improved more than comparison group I. A possible explanation for this is that comparison group I who did not get any guidance from their teachers on how to read the adapted articles became frustrated with the process.

Analysis of the change in students' reading strategies as reported by the students themselves indicates that the net gain of the experimental group was positive for the three strategies, albeit in decreasing order as the strategy is more sophisticated. In contrast, for the two comparison groups, all the strategies, except for "looking for meaning" in comparison group II, had negative net gain.

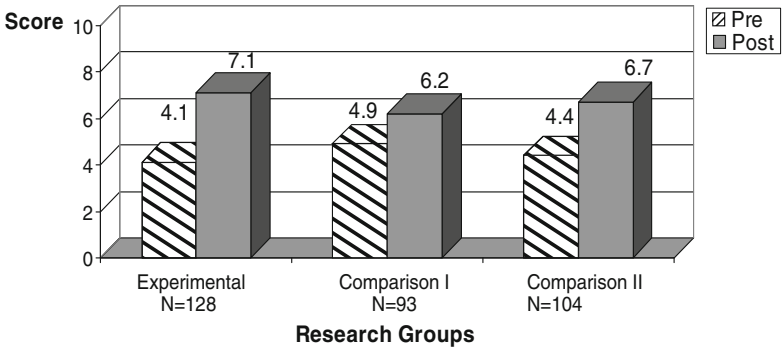

Fig. 8.8 Students' scores in the assignment of question posing

Cognition and Regulation of Cognition

Following the adapted article questionnaire (described before), student's cognition, as expressed in posing complex questions after reading the article, calls for a series of steps of applying guidelines for posing "good" or complex questions. Here we found that all three research groups improved their scores. The results, presented in Fig. 8.8, where the highest achievable score was 12 (maximum of 6 points for each one of the two posed questions), were normalized to a scale of 1–10. The experimental group students improved the complexity of the questions they posed significantly better than the two comparison groups (exp. > comp. I ~ comp. II, $F_{(2,322)} = 8.27$, $p < 0.0005$).

Reflection on the choice of posing the questions represents the regulation of cognition part of the metacognition. While there was no significant difference between the groups in the pre-questionnaire, in the post-questionnaire, the experimental students provided more high-quality reflection than the two comparison groups (exp. > comp. I ~ comp. II, $F_{(2,322)} = 5.27$, $p < 0.01$), implying that the metacognitive tool improves the regulation of cognition aspect of metacognition.

Conclusions and Discussion

Development of independent learners is an important science education objective (NRC 1996, 2005). To achieve this, learners need to know what they know and what they should know, so they can be in control of their learning process. This ability, in turn, is contingent upon well-developed metacognitive knowledge that students must utilize. The development and evaluation of science students' metacognition knowledge, learning processes, and self-efficacy are important for improving science education.

Despite evidence that metacognition is important for high-quality learning in science classrooms (Tobin and Gallagher 1987), there is often absence or lack of

classroom characteristics necessary for developing and enhancing students' higher-order thinking and metacognition. Overemphasis on memorization and other expressions of low-order thinking and learning is also common in schools (Zohar 2004). To improve this situation, educators need to be informed how they might harness pedagogical interventions to enhance students' metacognition (Thomas 2003).

Metacognition and the strategies and processes that students employ have been suggested to be subsets of self-regulation, which also includes self-efficacy and the extent to which individuals are confident in relation to performance of tasks or goal attainment (Schraw et al. 2006). Thomas et al. (2008) suggested that understanding students' science learning processes comprises their metacognitive science knowledge. Keeping this connection in mind, we have found that enhancing students' metacognitive knowledge improved their science learning process and understanding.

This chapter describes two studies investigating the effect of exposing high school chemistry students to metacognitive tools and strategies while reading a case study or an adapted scientific article designed as both a motivator and a platform for posing complex questions.

Table 8.9 presents a summary of the similarities and focal points of the two studies. Both studies were aimed at examining students' ability to pose questions after reading an adapted scientific article or a case study and the effect of using a metacognitive tool as part of this process. The first study was guided by case studies, while the second – by adapted scientific articles. The use of two levels of adaption of scientific articles, as specified in Table 8.1, enabled us to examine the metacognitive tool in the two studies across a variety of articles and student populations. While the first study researched the metacognitive processes related to question posing, the second one focused also on the reflection skill related to explaining the choice of the questions posed. Both studies used the question posing metacognitive tool for analysis of the posed questions based on the thinking level and chemistry understanding levels required to pose complex question. In the first study, we used the tool for question classification that is based on taxonomy, comprising content, thinking level, and chemistry understanding levels. In the second study we added (to the thinking level and chemistry understanding levels students were guided to use in order to pose a complex question) another factor we called contribution – the added value of the answer to the question posed for better understanding of the adapted article.

Based on these studies, we concluded that the metacognitive tool we had developed for use by students for posing complex questions enhanced their scientific understanding. In the first study, we found that students, who used the tool for planning the questions based on chemistry understanding levels and thinking levels, posed in the post-questionnaire more complex and deeper questions in comparison to the questions they posed in the pre-questionnaire. The second study demonstrated that the students who used the tool developed both knowledge of cognition and regulation of cognition.

The metacognitive process the students in the CCL environment (Study I), assisted by the metacognitive tool, underwent during practicing question posing is an important case of regulation or self-management of thinking (Jacobs and Paris 1987). Developing the ability to pose complex questions assisted by metacognitive

Table 8.9 Summary of the two studies similarity and focus points

Factor	Similarity	Study I focus	Study II focus
Research objectives	Examine students' ability to pose questions after reading a scientific article and the effect of using a metacognitive tool	Development of (1) question posing skill and (2) the related metacognitive processes	(1) Identification of students' reading strategies and (2) Development of (a) question posing skill and (b) the related reflection on the choice of the questions one posed
Question posing metacognitive tool	Analysis of the posed questions by thinking level and chemistry understanding levels	Question classification taxonomy based on content, thinking level, chemistry understanding levels, and interdisciplinarity[a]	Question monitoring based on thinking level, chemistry understanding levels and contribution – the added value of the answer to the question posed to better understanding of the article
Learning environment	High school chemistry classroom	Case-based computerized laboratory (CCL)	Regular chemistry classroom
Question posing motivation	Reading scientific articles	Reading case studies	Reading adapted articles
Participants Type	Chemistry students	Chemistry honors – 5 unit level	Chemistry majors – 3 unit level
Research groups		Focusing on the experimental group	Experimental and two comparison groups
Research tools and methodology	Pre- and post-questionnaires	• Pre- and post-case-based questionnaires – a quantitative approach • Students' semi-structured deep interviews – a qualitative approach	• Pre–post adapted article questionnaires • Pre–post reading strategies questionnaires
Main findings and conclusions	A metacognitive tool for posing questions can enhance students' scientific understanding	When planning via chemical understanding and thinking skills, students posed more complex and deeper questions and were able to evaluate and monitor their questions	The metacognitive tool was effective for both improving knowledge of cognition and regulation of cognition

[a]For more details about the interdisciplinarity category, see Dori and Herscovitz (2005)

knowledge is an important contribution for understanding chemical phenomena as well as scientific research. Our students experienced the three stages of regulation of cognition discussed by Jacobs and Paris (1987): *planning, evaluating, and monitoring*, as explained next.

The CCL students developed metacognitive strategies that helped them formulate higher-order-thinking questions. The students could *plan* in advance how to approach the question posing task and which questions would be considered complex. Interviews with students revealed that students were capable of *evaluating* and *regulating* the questions they had generated based on the taxonomy they had been taught. They were able to explain that inquiry questions can be defined as being at a higher level than knowledge and understanding. They evaluated questions which do not have a clear short answer but require detailed justifications as better and more complex questions.

When analyzing a self-posed question, students evaluated it by thinking level and by chemistry understanding levels.

Since the framework of the learning unit was computerized inquiry laboratories, students were exposed to formulating inquiry questions while planning and conducting inquiry experiments. In the process of posing questions about a case study, students transferred their skills from *planning* experiments by setting inquiry questions to the more general task of question posing after reading a case study. During the interview, students improved the questions they had posed initially. When probed by the interviewer, they went back to the taxonomy, and by *a regulation process*, they rephrased their questions to be more complex, focused and well-structured – a *monitoring* process. Students who were classified as having high metacognitive level developed better strategies than their peers for posing complex questions, which required higher-order thinking responses. There is thus an apparent relationship between one's high metacognitive knowledge and her/his ability to pose complex questions.

The contributions of the two studies described in this chapter are both theoretical and practical. From the theoretical aspect, we designed a metacognitive tool for posing complex questions and for developing reading strategies for understanding adapted scientific articles at various levels of difficulty (see Table 8.1). Our specially designed tool was found to improve students' metacognition – *knowledge of cognition and regulation of cognition*. In addition, the ability to pose complex questions assisted by metacognitive knowledge is an important contribution for improving students' understanding of chemical phenomena and scientific research.

From the practical aspect, the research findings of Study II have provided us with a solid basis for developing the learning unit titled *It's All Chemistry – Analyzing Adapted Scientific Articles and Case Studies* (Herscovitz et al. 2007b) which is aimed at exposing chemistry students and teachers for reading and understanding adapted scientific articles.

Combining our two studies and the metacognitive tool, we have developed and introduced a question complexity model for generating and classifying complex questions, which is summarized in Fig. 8.9.

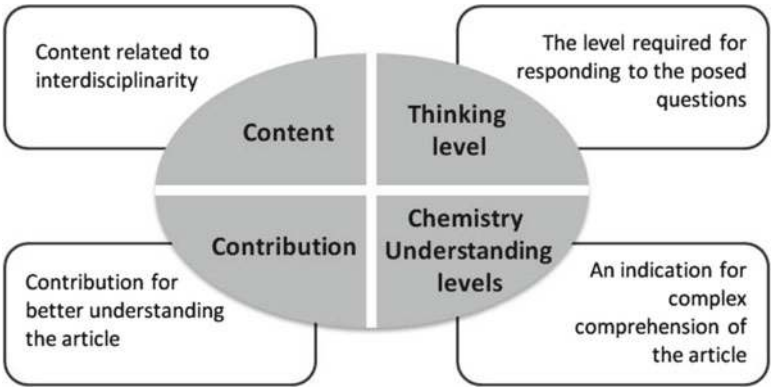

Fig. 8.9 Question complexity model for analyzing students' questions posed after reading adapted scientific articles

The question complexity model is based on four components, of which three – content, thinking level, and contribution – fit any scientific domain. The content component can be interdisciplinary (see also Table 8.1), concerning at least one additional scientific subject matter (other than chemistry) or some societal or economical aspects. However, the fourth component – chemistry understanding levels – is specific to chemistry. It is likely that other science disciplines have their own specialized components analogous to chemistry understanding levels.

The large scale of the studies (about 800 and 400 students in study I and study II, respectively), the two complexity levels of scientific articles adaptation, and the diversified array of research tools and learning environments provide us with a solid basis for drawing general conclusions that go beyond the specific settings of each research and the domain of chemistry. The metacognitive tool developed in these studies has proven to be effective in fostering both students' metacognition and their higher-order thinking skills of questions posing and reflection. We therefore recommend applying this tool and conducting additional studies to further explore its effect on science students' metacognition not just in chemistry but in other domains as well.

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Chapter 9
Explicit Teaching of Metastrategic Knowledge: Definitions, Students' Learning, and Teachers' Professional Development

Anat Zohar

Introduction

The call for teaching in general and for teaching science in particular in a way that will not focus merely on facts but will also foster students' thinking is by now several decades old (e.g., Adey and Shayer 1990, 1993; Bruer 1993; Feurstein et al. 1988; Halpern 1992; Lipman 1985; OECD 2009; Osborne and Dillon 2008; Pauls 1992; Perkins 1992, 1993; Resnick 1987). In recent years, this call is gaining momentum and increasingly finds its way into policy documents and classrooms. For example, a recent report concerning science education in Europe states that changing pedagogies from mainly deductive to inquiry-based methods is more likely to increase children's and students' interest and attainment levels:

> What is needed are science courses that engage students in higher-order thinking which includes constructing arguments, asking questions, making comparisons, establishing causal relationships, identifying hidden assumptions, evaluating and interpreting data, formulating hypotheses and identifying and controlling variables. (Osborne and Dillon 2008, p. 24)

Consequently, we can talk about two levels of science instruction. In the first level, which is still dominant in many classrooms, instruction is focused on transmission of facts and basic procedures for solving routine problems. Students are mostly engaged in tasks that require cognitive skills, such as memorization and following of routine algorithms. In the second level, the science curriculum is taught by engaging students in multiple tasks that require application of higher-order thinking strategies. In such second-level classrooms, students are often active learners who ask questions, solve problems, engage in inquiry, test scientific theories, discuss open-ended questions, construct models, etc. The routine use of thinking strategies (such as those

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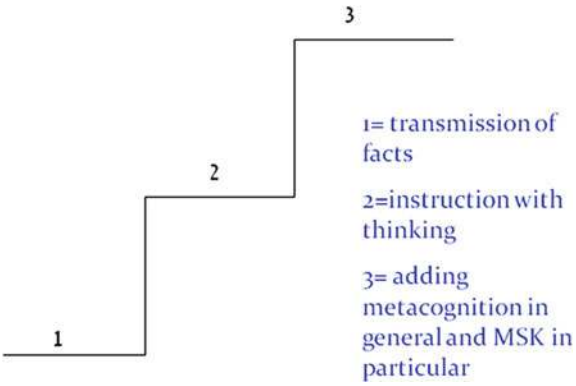


Fig. 9.1 A scheme of the Three levels of instruction

cited in the previous paragraph) in the course of learning generates a substantial transformation of classroom culture and discourse.

Yet, in classrooms that adopt these practices, thinking strategies are not necessarily viewed as explicit educational goals. For example, teachers may carry out inquiry activities without consciously thinking that they need to devote time to improve students' questioning abilities or their ability to control variables. Since thinking strategies are not viewed as explicit educational goals, they are usually not taken into consideration in the course of planning the science curriculum. It is the scientific content rather than thinking strategies that drives the organization and planning of the science curriculum in general and of individual science lessons in particular.

Educators know that in order to help students construct high-quality knowledge of complex scientific concepts, they need to plan instruction carefully and systematically using their pedagogical skills and expertise. Likewise, high-quality knowledge of thinking strategies can also benefit from systematic and well-planned instruction that applies advanced pedagogical principles. But because teachers don't usually think consciously about thinking strategies when they plan their lessons, this almost never happens.

We can however conceive of a third level of instruction in which thinking strategies are not only used but also addressed in the classroom in an explicit way (see Fig. 9.1). For example, teachers do not only require students to formulate questions or to control variables as part of a specific scientific inquiry process but also view these strategies as explicit educational goals and thus devote time to help students construct general knowledge that pertains to these two strategies. In this case, the teaching of specific thinking strategies becomes part of the explicit goals of instruction and is reflected in the design of particular lessons as well as in the design of larger instructional units. Thus, general knowledge about thinking strategies – i.e., what they consist of, as well as when, why, and how to use them – is taught in an explicit and well-structured way, thereby becoming an essential component of classroom discourse. Such general knowledge about thinking strategies comprises conscious awareness of the thinking strategies addressed during instruction. It is

regarded as a component of metacognitive knowledge which is called metastrategic knowledge (MSK, see detailed definition in what follows).

My claim is that adding MSK to routine instruction of higher-order thinking in science classrooms has substantial implications for the development of students' reasoning. The goal of this chapter is to examine this claim, its implications for instruction, and its implications for professional development. The chapter describes a set of studies addressing three different aspects of this idea: (1) the definition and conceptual analysis of MSK (Zohar and Ben David 2009), (2) the effects of explicit teaching of MSK on students' reasoning and, in particular, its effects on students with low academic achievements (Ben David and Zohar 2009; Zohar and Peled 2008; Zohar and Ben David 2008), and (3) issues pertaining to teachers' knowledge of MSK and to their professional development in this context (Zohar 1999, 2006). The following sections present an integrated review of the main ideas from this set of studies and discuss their implications for science learning.

Defining Metastrategic Knowledge

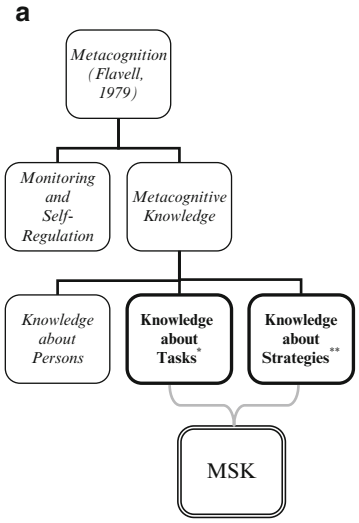
Metastrategic knowledge (MSK) is a subcomponent of metacognition that is defined as general knowledge about higher-order thinking strategies (Zohar and Ben David 2009). In addition to the list of thinking strategies cited from the recent report concerning science education in Europe (see opening paragraph of the "Introduction" on p. 197 above), other examples of such thinking strategies may include the ability to classify, to integrate knowledge from several different sources, to evaluate, to draw conclusions, to plan experiments, etc. Accordingly, most of the traditional inquiry thinking strategies are also considered higher-order thinking strategies. The pertinent metacognitive knowledge is an awareness of the type of thinking strategies being used in specific instances ("online" task-specific knowledge). Namely, in this context, the strategic level of thinking consists of higher-order thinking (HOT), while MSK refers to the metastrategic level of HOT. Although most of the components of this knowledge may be either implicit or explicit, its application in classroom instruction tends to be explicit because it is addressed by publicly discussing and negotiating its components during class discourse. The application of MSK in the classroom consists of the following abilities: naming the thinking strategy, making generalizations (making transition from "online" task-specific knowledge to general strategic knowledge), drawing rules regarding a thinking strategy, and explaining when, why, and how such a thinking strategy should be used, when it should not be used, what are the disadvantages of not using appropriate strategies, and what task characteristics call for the use of the strategy (Zohar and Ben David 2009).

Since the domain of metacognition is one that lacks coherence (Veenman et al. 2006), the relation of MSK to the overall concept of metacognition is not trivial. For instance, Flavell et al. (2002) divided metacognition into metacognitive knowledge and metacognitive monitoring and self-regulation. They then further divided metacognitive knowledge into three subcategories: (1) knowledge about persons,

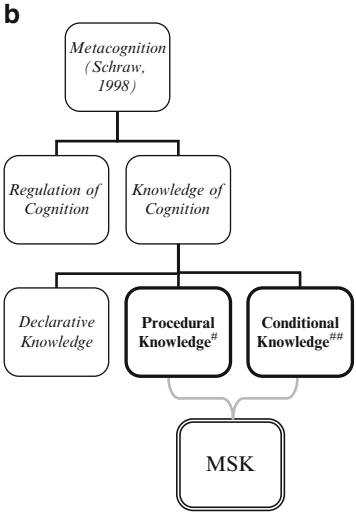
(2) knowledge about tasks, and (3) knowledge about strategies. The latter two subcategories are related to MSK because the task subcategory addresses the nature of the task demands (i.e., what task characteristics call for the use of the strategy or when to use the strategy) and the strategy subcategory concerns the nature of the strategies that are likely to succeed in achieving specific cognitive goals (i.e., why and how to use the strategy). MSK thus addresses the "When, Why and How" (WWH) of using a thinking strategy and is related to what Flavell termed "knowledge about tasks" and "knowledge about strategies" (see Fig. 9.2a).

Schraw (1998) made the distinction between knowledge of cognition and regulation of cognition. The former is further divided into (1) declarative knowledge, (2) procedural knowledge, and (3) conditional knowledge. MSK is related to the two latter subcategories. Procedural knowledge has to do with effective use of strategies (i.e., possessing a large repertoire of strategies, knowing how to sequence them and how to use qualitatively different strategies to solve problems). It is therefore closely related to the "how" component of MSK. Conditional knowledge refers, among other things, to knowing when and why to use strategies and is therefore closely related to the "when" and "why" components of MSK (Zohar and Ben David 2008, 2009, see Fig. 9.2b).

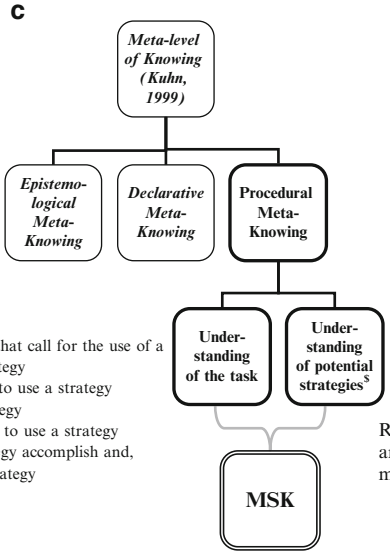
The definition applied in the present set of studies, however, is closest to the definition formulated by Kuhn who studied MSK in an extensive way (Kuhn 1999, 2000a, b, 2001a, b; Kuhn et al. 2004). According to Kuhn, the metalevel of knowing includes three subcomponents: (1) epistemological metaknowing, (2) declarative metalevel knowing, and (3) procedural metalevel knowing. The concept of MSK that is used in the present set of studies is tightly linked to Kuhn's procedural metalevel knowing, which addresses two main questions: (a) What do knowing strategies accomplish? (b) When, why, and how to use them? Kuhn proposes that metastrategic understanding consists of two components: One is the understanding and awareness of the nature and requirements of the task, and the other is the awareness and understanding of the strategies of one's repertory that are applicable to the task. Although our definition of MSK, indeed, addresses both the task and the strategy components that appear in Kuhn's definition, it is important to note that in the context of a study that addresses MSK publicly in the classroom (Zohar 2006; Zohar and Peled 2008; Zohar and Ben David 2008), it has a strong linguistic component that is absent in Kuhn's *Meta-level of Knowing* definition (Kuhn 1999). Please note that despite that difference pertaining to linguistic component, we view it as closely related to Kuhn's procedural metalevel knowing. Kuhn (1999, 2000a) makes a very clear distinction between procedural and declarative metaknowing. The distinction is based on the nature of the knowledge in the first-order cognitive level that is the object of the second-order metacognitive knowing and on whether or not that knowledge is an end to itself. Thus, the notion of MSK that is pivotal in the present research is procedural metaknowledge according to Kuhn because (a) the first-level cognitive knowledge that is its object is procedural (i.e., MSK is thinking about an effective *use* of a thinking strategy), and (b) rather than being an end to itself, this metaknowledge serves as means for enhancing the performance of a cognitive activity (Zohar and Ben David 2008; see Fig. 9.2c).



Relationships between MSK and the overall concept of metacognition, according to Flavell (1979)



Relationships between MSK and the overall concept of metacognition, according to Schraw (1998)



* Including task characteristics that call for the use of a strategy or "**when**" to use a strategy
** Including "**why**" and "**How**" to use a strategy
# including "**how**" to use a strategy
Including "**why**" and "**when**" to use a strategy
$ Including what knowing strategy accomplish and, when, why and how to use a strategy

Relationships between MSK and the overall concept of metacognition, according to Kuhn

Fig. 9.2 (**a**) Relationships between MSK and the overall concept of metacognition, according to Flavell (1979). (**b**) Relationships between MSK and the overall concept of metacognition according to Schraw (1998), (**c**) Relationships between MSK and the overall concept of metacognition according to Kuhn (1999)

Another conceptual area that requires clarification addresses the issue of the "fuzzy borders" between what is cognitive and what is metacognitive (Brown et al. 1983) or, as this issue had been formulated more recently by Veenman et al. (2006), the "disentanglement" of cognition and metacognition. In the case of the metacognitive knowledge that is the focus of our discussion, this issue has a special significance because it is particularly confusing when we come to examine it in the context of higher-order thinking. A significant question is whether or not higher-order thinking skills are themselves considered to be metacognitive. Prominent researchers in the field disagree on this issue. For instance, Flavell et al. (2002) view cognitive activities that comprise higher-order thinking, such as planning, as metacognitive skills. In contrast, Kuhn (2000a) views higher-order thinking activities as cognitive rather than metacognitive. One way for solving this contradiction is to follow the notion of Nelson (1996) and Nelson and Narens (1994), seeing the distinction between what is cognitive and what is metacognitive as relational rather than absolute. Accordingly, what consists of a metalevel activity in some circumstances may, in other circumstances, become a cognitive-level activity, depending on the context and focus of the activity. This implies that in discussing a specific component of metacognitive knowledge, it is imperative to characterize its context in order to establish whether according to the relationships between levels of thinking that exist in this specific context, it is indeed justified to refer to it as metacognitive rather than cognitive (for detailed explanation, please see Zohar and Ben David 2009).

The Effects of Teaching MSK

Rationale

My main argument is that maintaining the reality of general cognitive structures while teaching specific contexts may be a very powerful educational means for bringing about change in students' reasoning. There may be a variety of pedagogical ways for teaching MSK, such as reflecting on others' performance on a task or engaging in a series of written metalevel exercises (see Kuhn et al. 2004). Nevertheless, the pedagogical way embraced in the present set of studies is engaging in *explicit teaching of MSK*.

It is important to note that by explicit instruction of the knowledge entailed in MSK, we do not mean "transmission of knowledge" or rote learning. Our general educational belief is that knowledge must be actively constructed by the knower in order to be meaningful and useful. This belief extends not only to the learning of concepts and strategies (Zohar 2004) but also to the learning of metastrategies. Thus, although our instruction has a strong verbal component, the explicit teaching of MSK is designed to trigger the learner to conduct active thinking and to foster deep understanding. In the context of school teaching and learning, MSK has two important characteristics. The first is that it has a strong linguistic component that can be put into words, i.e., formulated as statements that may be individually and socially negotiated. The second is that it must be strongly supported by experience. Since this type of knowledge is highly abstract, it is unlikely that most students will

be able to understand it without engaging in a series of practical experiences. In this sense, addressing rules, generalizations, and principles of good thinking always needs to be connected to students' concrete experiences in which they use a thinking strategy rather than addressing it only in an abstract way. In fact, good instruction in this area involves a constant movement between the formal, abstract level and multiple concrete experiences that students encounter over and over again as they progress through the science curriculum.

Another important issue that needs to be considered in relation to the teaching of higher-order thinking in general and of MSK in particular is its possible value for improving higher-order thinking of students with low academic achievements. Fostering the thinking of an elite group of students had been the goal of many educators since ancient times. The novelty in recent educational curricula is the aspiration to foster reasoning and deep understanding in *all* young people (Resnick 1987; Rutherford and Ahlgren 1990; Millar and Osborne 1998; Qualifications and Curriculum Authority, retrieved 2005; Zohar and Dori 2003). Research findings, however, show that students who have low academic achievements are less likely to receive instruction whose goal is to foster higher-order thinking than students with high academic achievements. Raudenbush et al. (1993) revealed that teachers in classes of high-achieving (HA) students are substantially more likely to emphasize higher-order processes than teachers in classes of low-achieving (LA) students. Zohar et al. (2001) found that many teachers who believe that teaching higher-order thinking is an important educational goal for HA students believe that higher-order thinking is inappropriate for LA students who should be taught by a transmission of knowledge approach. Similar findings were obtained by Warburton and Torff (2005). This state of affairs is troubling because it turns out that precisely those students who may need the most support in order to develop their reasoning abilities are being deprived of equal educational opportunities in this field. Furthermore, teachers' beliefs that higher-order thinking is inappropriate for LA students may become a self-fulfilling prophecy.

At least one of the reasons for such teachers' beliefs and behaviors is a feeling that they lack satisfactory instructional means for teaching thinking to students with low academic achievements (Zohar et al. 2001). Therefore, it is imperative to develop appropriate instructional means to address this goal, and to assess their effects for LA students. Previous studies in both science and mathematics education show that metacognitive instruction is highly beneficial for low-achieving students (Cardelle-Elawar 1995; Mevarech and Kramarski 1997; White and Frederiksen 1998, 2000; Mevarech 1999; Kramarski et al. 2002; Teong 2003). The findings of these studies suggest that MSK may also be a suitable teaching strategy for low-achieving students.

Study 1: Controlled "Laboratory" Condition

To further explore this issue, my research group initiated a set of three studies designed to explore the conditions under which explicit instruction of MSK would be effective and, in particular, how it would affect the thinking of LA and HA students. Since the design and instrumentation of the three studies are quite similar, a detailed

account of all three studies would be tedious in this chapter. Therefore, I chose to describe study 2 in a more detailed way, while providing only a brief description of studies 1 and 3. My main purpose in the brief description of studies 1 and 3 is thus to emphasize the unique contribution of each study to the overall picture that came out of the research project as a whole.

The first study (Zohar and Peled 2008) assessed the effects of explicit teaching of MSK regarding the control-of-variables thinking strategy on gains of low-achieving (LA) and high-achieving (HA) 5th graders. The study took place in controlled laboratory conditions where a relatively small group of students ($n=41$) participated in an intensive, long-term, one-to-one interaction with an experimenter. The findings showed that students in the experimental group (who received the explicit MSK teaching) scored higher than students in the control group in a measure of strategic knowledge as well as in a measure of MSK. Gains were preserved in near and far transfer tasks immediately after the end of instruction and 3 months later. Explicit teaching of MSK affected both LA and HA students, but it was extremely valuable for LA students. The data also showed that LA students required a longer period than HA students to reach their top score. This finding has significant implications for the design of instruction for LA students.

Study 2: Moving to Real Classroom Conditions

However, study 1 was conducted in "sterilized" laboratory conditions that are very different from the "messy" conditions that exist in real classrooms in which one teacher is often responsible for the learning of 30 children. In addition, that study addressed only the control-of-variables thinking strategy, and therefore, the findings could not be generalized to other thinking strategies. In order to be able to find out whether the findings of the laboratory-conditions study would be repeated in an authentic school setting, a new study was required. The new study extended the previous one in two ways: (a) It was conducted in natural, authentic school conditions (rather than in a laboratory with carefully controlled conditions and a one-to-one ratio between the experimenter and each student), and (b) it extended the goals of the previous study by examining the effects of explicit teaching of MSK not only on the control-of-variables (COV) thinking strategy but also on two additional strategies: defining research questions (DRQ) and formulating research questions (FRQ) (Ben David and Zohar 2009; Zohar and Ben David 2008).

The goal of the authentic school setting study was to examine three research questions:

1. What are the effects of explicit teaching of MSK in authentic school setting regarding the COV, DRQ, and FRH thinking strategies on students' performance?
2. How does such explicit teaching of MSK regarding the three strategies affect delayed transfer (retention)?
3. What are the differences between LA and HA students concerning questions 1 and 2?

Participants were 119 school students aged 13–14 years (45 boys and 64 girls) who studied in six 8th grade classes of the same public school in a large city. The six classes were randomly divided into experimental and control conditions. In addition, students in each class were classified as either HA or LA based on their mean academic scores as expressed in the report cards they received at the end of 7th grade. We thus had a total of four experimental subgroups in a 2 × 2 design: LA experimental subgroup ($n = 30$), LA control subgroup ($n = 29$), HA experimental subgroup ($n = 30$), and HA control subgroup ($n = 30$).

The study was designed as part of a curriculum in which the biological topic of reproduction was taught by using a set of consecutive short inquiry learning activities taken from the Thinking in Science Classrooms (TSC) project (Zohar 2004), adapting them for the purposes of the present study. The curriculum was taught over a period of 22 science lessons. In some of these lessons, students worked individually or in small groups. All students engaged for the same amount of time in various scientific inquiry tasks that required, among other things, the three scientific thinking strategies (COV, DRQ, and FRH). Only students in the experimental subgroups received explicit instruction about MSK in the context of the three thinking strategies. The first 12 lessons focused on the COV strategy. The remaining ten lessons focused on the DRQ and FRH thinking strategies. In what follows, I shall describe the part of the study pertaining to the COV strategy in detail and then summarize the part of the study pertaining to the two additional thinking strategies.

During learning of the COV strategy, students engaged two computerized inquiry tasks as well as noncomputerized inquiry tasks whose topics matched subjects from the 8th grade science curriculum. As explained earlier, teaching MSK was indeed the goal of the intervention, but teaching applied methods of knowledge construction rather than knowledge transmission (see below).

A written test to assess students' ability to use variable control was given on two separate occasions: a pretest was given before the beginning of instruction and a posttest was given after the completion of instruction. An additional written test to assess delayed transfer (retention) took place three months after the completion of instruction. The tests assessed both strategic and metastrategic knowledge. The items addressing strategic knowledge were coded according to an adaptation of the coding scheme developed by Kuhn et al. (1992, 1995). The items addressing metastrategic knowledge were coded by using the coding scheme developed by Kuhn and Pearsall (1998).

Study 2: Description of Instruction

In order to give the reader a better sense of what I mean by explicit teaching of MSK that is designed to help the learner construct deep understanding of thinking strategies, I provide an example, documenting how instruction has both a strong linguistic component and a connection to students' concrete experiences. In this example, students in fact need to use the thinking strategy rather than only to address thinking strategies in an abstract way.

The intervention consisted of two parts: (a) a short unit of instruction about MSK that took place in the forum of an entire class (with approximately 30 students, for approximately 45 min) and (b) probes given during individual students' engagement with the inquiry tasks. The short unit of instruction focused on a demonstration followed by a discussion of various components of metastrategic knowledge regarding the control-of-variables strategy. The teacher demonstrated an experiment in which she purposely failed to control variables. She put a lamp on her desk and invited one of her students to light it. When the light did not come on, the teacher changed the light bulb and strengthened the plug to the wall. This time, when the student tried to light the lamp, she succeeded. The teacher then initiated a discussion about "why did the light not come on?," "Can we know for sure what was the reason for this?," "Why?," "What do we have to do in order to know for sure?," etc. Through such questions, the teacher directed the discussion by leading students to think about the significance of using the control-of-variables strategy. She directed students to articulate various issues pertaining to this thinking strategy; to formulate generalizations; and to explain when, why, and how to use the control-of-variables strategy.

There are two differences between the lamp demonstration and the problems students need to solve in the course of the scientific inquiry tasks they encounter in class. The first difference is that the lamp demonstration is taken from the domain of everyday life rather than from a formal science content. The second difference is that it addresses control of variables in a case with only two variables rather than with multiple variables, as is often the case in scientific inquiry. Many of the students who cannot yet control variables in the context of complex scientific inquiries have intuitive knowledge of the issues involved in the relative simple case of controlling the two variables in the context of the lamp demonstration. The teaching unit thus extracts students' intuitive prior knowledge, using it through a process of guided discussion to build more formal knowledge of the control-of-variables strategy.

For many students (especially those who were classified as high achievers; see above), part 1 of the intervention was sufficient for learning to control variables successfully. However, for other students, this was not the case. The second part of the intervention consisted of probes given to individual students who failed to control variables while they were working on solving various problems related to inquiry. When the teacher diagnosed a student who, in the course of his or her investigation, had failed to control variables, she asked a series of guiding questions, such as: "Do you remember the experiment with the desk lamp?," "Do you see any similarities between that experiment and the problem you are investigating today?," "Do you think that you are using the rule that we had studied in the previous lesson?," "What can you do to improve your current investigation?," etc.

For instance, in one of the lessons, Ben was using a computerized microworld that enabled him to make a series of experiments in order to discover which of several variables affected the rate of seed germination (Zohar and Ben David 2008). The teacher diagnosed that Ben failed to apply the control-of-variables rule: He wanted to find out whether adding water makes a difference, but he designed an experiment

with a different type of seed in each test tube. The following conversation then took place between the teacher and Ben:

1. Teacher: Can we draw a valid conclusion?
2. Ben: No, because they [i.e., in the first given experiment, taken from a written activity] did not control variables….. [but] I did control variables because I put the same things in each test tube.
3. Teacher: So can we draw a valid conclusion from your experiment?
4. Ben: Yes, because there is control of variables.
5. Teacher: Do you remember what we had learned from the experiment with the desk lamp?
6. Ben: Yes. That we need to control variables….That we need to do it one thing at a time and not to mix everything together…. To leave all the features the same and to change only one feature and then we would know that this feature makes a difference.
7. Teacher: Do you see any similarity between the desk lamp experiment and the experiment you suggested here?
8. Ben: It's the same thing.
9. Teacher: Is this what you did here? Used control of variables? [pointing to the table with the experimental design which Ben created]
10. Ben: Yes. Here you can see that I did everything… and here… [long pause]… here I…. I don't know…
11. Teacher: Think… Did you apply the control-of-variables rule?
12. Ben: Here… I think… I think I should have… Perhaps I should have used the same kind of seed in all test tubes….

Ben obviously remembered the lamp demonstration and could recite the general knowledge stating how to apply the COV strategy (see line # 6). However, this transcript illustrates the gap between Ben's ability to recite the control-of-variables rule and to apply it correctly. The teacher led Ben to realize the disparity between the rule and his experimental design and helped to destabilize his conviction in the correctness of his work (see line # 10). Finally, the teacher (see line # 11) guided Ben in constructing the correct thinking strategy (see line # 12). From this point onwards, Ben actually did succeed in carrying out the COV strategy. This excerpt thus demonstrates that for some students, it is crucial to accompany part 1 of the intervention by the individual teachers' intervention centering on concrete cases of reasoning.

While students in the experimental group received parts a and b of the intervention, students in the control group received instead, and for the same amount of time, instruction that related to the content rather than to the thinking elements of the activity. Instead of part a, the control group students received a short unit of instruction about seed germination, which is the topic of the relevant computerized task. Instead of part b and in order not to create a difference between the experimental and control students in the sense that only the experimental group students would have the opportunity to benefit from a teacher–student interaction,

we implemented a parallel teacher–student interaction in the control group that addressed elements of content rather than of MSK.

It is important to note that although the type of instruction we suggest has to do with inquiry learning, it is not intended to replace authentic, "hands-on," scientific inquiry nor the authentic learning environment that may result when students are engaged in trying to make sense of scientific articles, data, and evidence that are embedded in rich science content. However, authentic inquiry or discussions of scientific research and evidence that take place in classrooms are often questionable in terms of the quality of the reasoning processes that children perform. Many examples of students' work describing reasoning within "authentic" learning environments may have some superficial similarity to scientists' work, but have little in common with the deep logical structures of sound scientific investigations. It is precisely the value and significance of "hands-on" experiments, authentic inquiry, and authentic sensemaking of scientific research embedded in rich science contents that make it important to devote time and energy for helping children to improve their understanding of its many facets, including the reasoning component that characterizes scientific inquiry. It is precisely, the complexity, the "messiness," and the multilevels involved in authentic science learning that often make it difficult to attend to the quality of reasoning strategies. The learning environments that are created while students engage in authentic learning are often too rich and distracting for that purpose. There are too many things going on simultaneously, and it's hard to focus students' (and teachers') attention on the careful thinking required for understanding the logical elements of scientific inquiry. Teaching reasoning strategies is a highly complex educational goal. As is the case with any other complex educational goals, it needs careful planning and focus.

The instructional methodology proposed in this chapter, i.e., carefully planned instruction focusing on metastrategic knowledge, needs to be situated in this context rather than treated as stand-alone or as substituting authentic scientific inquiry. It should be viewed as one component of a curriculum that is rich in scientific thinking, argumentation, and inquiry in authentic contexts. It is hoped that as the language of thinking and the reality of explicit reasoning strategies will find their way into the classroom, teachers will be able to make continuous connections between MSK and the "authentic," content-rich activities that take place in the class, thereby supporting students' understanding of these activities by more sound reasoning strategies.

Study 2: Results

Data analysis of the pretest in the experimental and control groups showed that the two groups (not divided to subgroups according to students' academic level) had similar scores and the small difference between them was not significant (Mexp = 0.70, SD = 0.92; Mcon = 0.75, SD = 0.97; $t(117) = -0.26$; $P > 0.05$), indicating that before the intervention, students from both groups demonstrated the same

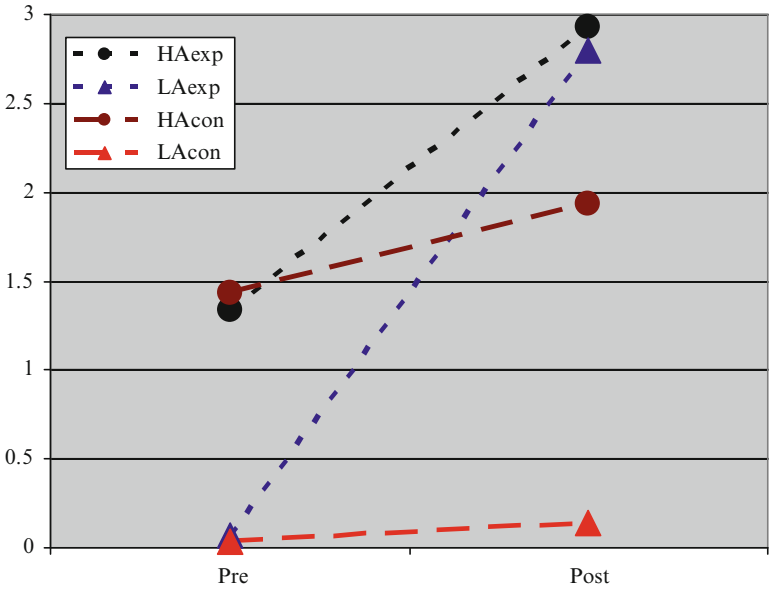


Fig. 9.3 Strategic level in the 4 subgroups: mean score of HA and LA students in pretest and posttest ($n = 119$)

strategic level. In the posttest, the mean score of the experimental group (Mexp = 2.87, SD = 0.46) was higher than the mean score of the control group (Mcon = 1.05, SD = 1.19). A repeated measures ANOVA showed (a) a significant main effect for time $F(1,117) = 188.44$; $P < 0.001$, indicating a difference between the pretest and posttest in the mean score of all students; (b) a significant main effect for treatment $F(1,117) = 37.56$; $P < 0.001$, indicating the effect of the metastrategic intervention; and (c) a significant interaction effect between time and treatment $F(1,117) = 106.89$; $P < 0.001$, indicating that the gain of students in the experimental and control groups was different across time. These results show that even students in the control group improved the quality of their thinking. This indicates that even just engaging in an inquiry task on the cognitive level contributes to gains in students' reasoning abilities. However, students in the experimental group – who similarly engaged in the inquiry task on the cognitive level but, in addition to that, received the metastrategic explicit instruction – had significantly larger gains in terms of the quality of their thinking.

What do the findings tell us about students' gains when we examine the data divided into the four subgroups (LA experimental, LA control, HA experimental, and HA control)? The results are presented in Fig. 9.3.

Figure 9.3 presents the scores of the four subgroups in the written pretest and posttest. The graph shows that in the pretest, students from the two LA subgroups demonstrated the same strategic ability and the small difference between them was not significant (Mexp = 0.07, SD = 0.25; Mcon = 0.03, SD = 0.18; $t(57) = 0.55$; $P > 0.05$). The scores of students from the HAexp and HAcon subgroups were also

similar to each other (Mexp = 1.33, SD = 0.92; Mcon = 1.43, SD = 0.93; $t(58) = -0.41$; $P > 0.05$), indicating that prior to the intervention, the level of students from the two LA subgroups was the same and the level of students from the two HA subgroups was the same. Nevertheless, the pretest mean score (combined from scores of students in the experimental and the control groups) of the HA students ($M = 1.38$; SD = 0.92) was significantly higher than the mean score (combined from the scores of students in the experimental and the control groups) of the LA students ($M = 0.05$; SD = 0.22; $t(65) = 10.87$; $P < 0.001$), confirming that before the intervention, HA students demonstrated a higher strategic level than LA students.

In the posttest, students from three subgroups (HAexp, LAexp, and HAcon) made considerable progress compared with their pretest scores. Students from the LAcon group made no progress. The posttest score of HAexp students ($M = 2.93$; SD = 0.36) is higher than the posttest score of HAcon students ($M = 1.93$; SD = 1.04). However, a larger gap is found between the posttest score of LAexp students ($M = 2.80$; SD = 0.55) and LAcon students ($M = 0.14$; SD = 0.35). Moreover, the posttest score of LA students from the experimental group is higher than the score of HA students from the control group and is close to the score of the HA students from the experimental group. Therefore, the data show that the largest pretest-to-posttest gain was for LA students in the experimental group.

To test the significance of the differences between mean scores of the four subgroups, we conducted a 2 × 2 × 2 (treatment × student level × time) repeated measures ANOVA. The findings showed (a) a significant main effect for treatment $F(1,115) = 100.03$; $P < 0.001$, indicating the effect of the metastrategic intervention; (b) a significant main effect for student level $F(1,115) = 163.43$; $P < 0.001$, indicating differences between LA and HA students; and (c) a significant interaction effect between treatment and student level $F(1,115) = 24.92$; $P < 0.001$, indicating that the metastrategic intervention affected LA and HA students differently.

A parallel analysis was conducted for students' knowledge on the metastrategic level. The general pattern of the results was similar to that of the findings on the strategic level: In the pretest, LA students from both the experimental and control groups had a significantly lower metastrategic score than HA students from both the experimental and control groups (Zohar and Ben David 2008). However, in the metastrategic posttest, students from the LA experimental group had the largest gain, and their score was even higher than that of students from the HA control group.

A possible argument that could undermine these findings is that perhaps students' gains were obtained because their intense practice with the task made them learn correct patterns of reply by rote. To examine this argument, students were given a delayed transfer task three months after the completion of instruction. The results are presented in Fig. 9.4.

The data show that 100% of the HAexp students drew a valid inference in the transfer test compared to 90% of LAexp, 36.7% of HAcon, and 0% of the LAcon students. These findings indicate that the effect of the treatment was preserved for a different task three months after the end of instruction.

Finally, the findings from the written test items that addressed two additional thinking strategies – defining research questions (DRQ) and formulating research hypotheses

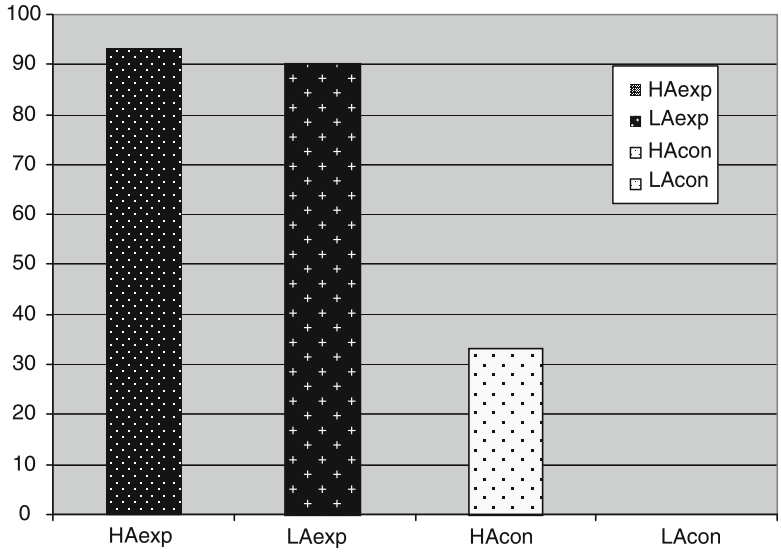


Fig. 9.4 Strategic level in the 4 subgroups: percentage of students who drew a valid inference in delayed transfer test ($n = 119$)

(FRH) – followed the same pattern as described earlier for the results regarding the control-of-variables (COV) thinking strategy: The strategic scores of the experimental and control groups were very similar in the pretest, and the small differences were not statistically significant. However, in the posttest and in the delayed transfer test, students from the two experimental subgroups (HAexp and LAexp) made considerable progress compared with their pretest scores. In the posttest and delayed transfer test, HA students in the experimental group scored highest of all subgroups – followed closely by LA students in the experimental group, who scored higher than the HA students in the control group and much higher than the LAcon students. Similar to the findings from the control-of-variables strategy, these differences concerning the DRQ and the FRH strategies were also statistically significant.

Teachers' Knowledge and Professional Development

Background: What Do Teachers Need to Know and to Be Able to Do?

Recent studies highlight the fact that teachers find enacting a pedagogy for metacognition difficult. It is not trivial for them to take up research-based ideas in this field unless they are translated into practical recommendations (Leat and Lin 2007). However, despite the role of metacognition in student success, only limited research

has been done to explore teachers' and preservice teachers' awareness of their metacognitive knowledge and pedagogical understanding of metacognition, and of their ability to make progress in these types of knowledge following professional development (Abd-El-Khalicka and Akerson 2009; Kramersky and Michaslky 2009; Wilson and Bai 2010). This section aims to address teachers' knowledge and professional development in the context of MSK.

In the previous sections, we saw that the application of MSK in the classroom is extremely significant for students' learning. This finding indicates how important it is for science teachers to be able to use MSK appropriately in the classroom, raising serious concerns regarding their pertinent knowledge: What do teachers need to know and to be able to do in order to apply MSK successfully in the classroom? Do teachers usually possess the pertinent knowledge? Can professional development (PD) help teachers learn what they need to know in this area?

Let's start at the end point. In order to apply MSK successfully in the classroom, teachers need to do the following:

- To model the use of general thinking structures in a variety of specific circumstances that call for the application of higher-order thinking strategies, moving continuously between the levels of cognitive and metacognitive knowledge;
- To scaffold students' use of general thinking structures in a variety of specific circumstances, moving continuously between the levels of cognitive and metacognitive knowledge;
- To provide opportunities for students to articulate the cognitive processes they apply during problem-solving;
- To introduce the "language of thinking" into the classroom and to make sure that it will become an inherent component of routine classroom discourse;
- To design and then teach careful and thoughtful learning activities in which thinking goals are made explicit;
- To engage in long-term and systematic planning of thinking activities across several sections of the science curriculum that will facilitate repetitive application of the same thinking strategies in various contexts, discussing their general characteristics using a variety of pedagogical means.

The final point requires additional clarifications. In long-term planning, teachers should make sure that the same thinking patterns are repeated over and over again in different scientific topics so as to prevent the "welding" of the thinking skill into a specific context, thereby enhancing transfer. Thus, during the school year, as different chapters of the curricula unfold, a specific thinking pattern would be addressed repeatedly through different science concepts using a variety of pedagogical means. This purpose can be accomplished by many alternative routes. Teachers may ask students to reflect upon a thinking process they have used in solving a certain problem, coaching them in articulating general aspects of the thinking patterns they have used. Alternatively, after students had the opportunity to engage in the same thinking pattern across several particular different contexts, teachers may bring up all these situations, asking students to find their common denominator. Such a discussion addressing general elements of a thinking pattern may lead to making generalizations

and to formulating rules regarding this thinking pattern. Preferably, teachers will lead their students to formulate the generalizations and rules by themselves. Such teaching sequences present an inductive approach to the teaching of MSK. Using another technique, teachers can also present students with a list of thinking patterns, and following a "thinking activity," ask students to match specific thinking patterns with various parts of the activity. Alternatively, teachers can also use a deductive approach, i.e., to first present the general MSK pertaining to a thinking strategy and only then present specific cases requiring the application of this strategy. There are therefore many possible routes to addressing MSK in the classroom, but the main thing is that teachers will navigate their students back and forth between the concrete and abstract levels, with a strong emphasis on articulation of the cognitive activities being employed.

What type of knowledge do teachers need in order to be able to do all this in the classroom? First, it is clear that teachers cannot address MSK in their practice if they do not possess that type of knowledge themselves. MSK is thus a body of knowledge that teachers must be familiar with in order to address it in class in a sound way. In addition, as many studies show, familiarity with whatever it is that one is supposed to teach might be a necessary condition, but it is certainly not a sufficient condition for teaching. Pedagogical knowledge, i.e., the ability to use that knowledge in the classroom in multiple ways, is also required. In order to understand the nature of this knowledge, we need to turn to the large body of literature that, following Lee Shulman's work (e.g., Shulman 1986, 1987; Wilson et al. 1987), addressed various components of teachers' knowledge (e.g., Adams and Krockover 1997; Cocharn and Jones 1998; Gess-Newsome and Lederman 1999; Van Driel et al. 1998). However, the traditional distinction made in this literature between subject matter knowledge, pedagogical content knowledge, and general pedagogical knowledge is fuzzy and unclear when we try to apply it to the context of teaching higher-order thinking in general and to MSK in particular. An innate difficulty exists in referring to the pedagogical knowledge teachers have in this field either as pedagogical content knowledge (that tends to be embedded in specific subject matters) or as general pedagogical knowledge (that tends to be independent of specific subject matters). It seems that because of the special nature of the type of knowledge under consideration, none of the prevalent existing constructs is appropriate. An elaborate discussion of this topic is beyond the scope of the present article and can be found elsewhere (Zohar 2004, Ch. 6), where I suggested addressing teachers' pedagogical knowledge in relation to instruction of higher-order thinking by a special term: *pedagogical knowledge in the context of teaching higher-order thinking* (Zohar 2004). This term highlights the fact that pedagogical knowledge in this field has some unique characteristics. At the same time, this term does not imply a commitment to treat this knowledge as either content-specific or general. Many of the specific characteristics of this knowledge pertain to the teaching of MSK, such as the knowledge required for carrying out the specific classroom activities pertaining to the teaching of MSK described earlier. Clearly, this knowledge consists of an amalgamation of knowledge about MSK with some specific pedagogical knowledge regarding how to actually address MSK in the classroom.

Methodology for Study of Teachers' Knowledge and PD

Two studies (Zohar 1999, 2006) were conducted in order to investigate the research questions that were described earlier (see page 16) about teachers' initial knowledge and their learning following professional development. The two studies took place in professional development courses that were taught in the context of the Thinking in Science Classrooms (TSC) project (Zohar 1999, 2006). The project's goal was to implement instruction of higher-order thinking strategies as a routine component of teaching in the junior high school science curriculum. The project consisted of a series of learning activities that were especially designed to integrate teaching of thinking strategies with the teaching of various science topics. As part of the project, numerous professional development courses took place in several locations. These courses varied in length from 24 to 56 academic hours (the length was usually determined by the organization which ordered the course), providing a convenient environment for the study of teachers' knowledge. During the basic 24-h course, teachers discussed instructional goals and learned some basic theoretical concepts related to instruction of higher-order thinking (e.g., transfer and metacognition), became acquainted with specific examples of the TSC learning materials and analyzed the instructional methodologies they consist of, and discussed various aspects of classroom implementation. Additional activities that took place in the longer courses consisted mainly of (a) *creative workshops* in which groups of teachers composed new learning activities to be used in their own classrooms and (b) *reflective workshops* in which teachers reflected on actual classroom implementation.

In the courses that were examined in the first of our two studies of teachers' knowledge, MSK was not addressed in an explicit way. Also, data collection in this study was based on products generated by learning processes that took place naturally during teachers' learning processes throughout the courses. Data collection therefore took place by the following three means: (a) All discussions from two courses (one of 24 and the other of 40 h) were audiotaped. Thirty-seven teachers participated in the two courses that were audiotaped. (b) During seven courses (including the two courses which were audiotaped), notes were taken by the leader, describing meaningful events. The total number of teachers who participated in those seven courses was 163. (c) Elements from teachers' written work that referred to metacognition were collected.

Following the findings from the first study, changes were made to the curriculum of subsequent courses. Consequently, issues pertaining to MSK were explicitly incorporated into subsequent courses. Therefore, in the courses that were examined in the second study, ideas pertaining to MSK were integrated into all sections of the course (see explanation of level 3 instruction on p. 2 and in Fig. 9.1); this was carried out by the use of diverse teaching methods, such as short lectures regarding theoretical issues pertaining to metacognition and/or MSK, solving problems with an explicit metacognitive and/or MSK component, reflecting upon and discussing the rationale of such learning activities, and reflecting on classroom activities that had a component of MSK embedded in them.

Another difference between study 1 and study 2 was in the data collection. In addition to collecting the natural products of teachers' learning, study 2 focused on a small group of 14 teachers and followed them closely, employing two sets of classroom observations and two sets of individual interviews: The first set took place before the beginning of the course, and the second after its completion. Interviews took place following a lesson in which the interviewer observed a lesson that the teacher had previously planned as a "thinking lesson." Most interviews were approximately 45 min long. The interviews were rather comprehensive and referred to many elements of teachers' knowledge in the context of teaching higher-order thinking skills. Two of the interview items are relevant to the study described here: (a) Do you engage your students in learning to think? If so, how do you do that? (b) Which thinking skills do you emphasize in your teaching? In addition, teachers were asked to reflect on the lesson they had taught and, among other things, to explain which thinking skills they addressed during that lesson. The analysis of the processes that took place during instruction, as well as the comparison of data from the early and late classroom observations and teachers' interviews, made it possible to document developments in the knowledge of these 14 teachers as they made progress with their learning in the PD course and with trying out new ideas in their classrooms along the school year.

The teachers who participated in the two studies were Israeli junior high school and/or high school science teachers who participated in the TSC courses. Teachers came to the courses either because they were sent by their principals, superintendents, or department chairs or because they chose this particular course from a list of professional development courses offered to them each year. In both cases, participation granted professional credit. Accumulation of a certain amount of credits resulted in a significant raise in salary. The subjects in this study did not constitute a random sample. Since many of them had chosen to participate in the TSC courses because they were interested in the topic and thought it was important for their work, we can assume that our subjects are a self-selected group which is probably more inclined toward an innovative educational experience, such as the TSC project, than a representative sample of science teachers would be.

Findings: Teachers' Initial Knowledge of MSK

Is science teachers' initial knowledge (i.e., the knowledge they posses prior to participation in professional development in this field) sufficient to support the desired classroom activities described earlier? Extensive findings from our two studies show that the response to this question is negative and that teachers' initial knowledge concerning MSK was lacking and unsatisfactory for the purpose of instruction. Let us start by noting some trends that came up in study 1 in the responses of teachers when asked (in the courses' concluding session) to summarize what they saw as the most important things they had gained from the course (Zohar 1999). Since the comments presented below were made by teachers during a class discussion, the

sentiments expressed may have been influenced by a desire to please the instructor. However, please note that these quotations were not brought for the purpose of showing whether or not teachers liked the course (an issue that is likely to be influenced by social desirability), but to learn about what components of the course the teachers saw as more valuable than others and about their perception of how the course had affected them (and not whether or not it had affected them). Teachers were not prompted to talk specifically about metacognition, and most of what they had to say on the subject were not things that they may have heard during the course. In fact, some of what they had to say indicated considerable difficulties and even failures on their part. Therefore, apart from the issue of whether or not teachers liked the course (which is a side issue in these excerpts), it is hard to imagine why they would choose to say about metacognition precisely the things they have said unless it represented their genuine experiences.

Some teachers referred to metacognition as an exceptionally valuable thing they had learned:

> I've learnt a lot. Particularly about the issue of metacognition

> The course was very good. The part about metacognition was important

Other teachers responded by expressing the idea that before the course, they were teaching for thinking in an "intuitive" way. The course made them conscious of teaching higher-order thinking as a distinct educational goal, enabling them to deal with teaching thinking in a more structured and focused way. The following excerpts are examples of that idea:

> Perhaps I was doing it intuitively, but now, things are more structured and well arranged for me

> I think I went through a real process. I think that my awareness of things was sharpened a great deal. I think that part of what we got here - a large part of it we were all doing intuitively - but making it conscious - I think this is the greatest thing I gained. That I will know what I am doing in a focused way is what I see as the most meaningful thing. Because it is completely different. Because your work is planned in a completely different way

> Gaining experience with "thinking lessons" and the necessity to stop and think … one moment, what am I doing from the point of view of thinking? Am I doing it right? It boosts up my self confidence and clearly also increases the level of other lessons I teach

As can be seen in the next excerpts, the consciousness of thinking as a distinct educational goal, and the ability to engage students with metalevel activities of thinking skills, was seen by teachers as related to their newly acquired metacognitive knowledge of thinking skills:

> [what changes is ….] the focus on thinking. I used to do it in my lessons (before the course), but I never called thinking skills by their names, and I never expected my students to know that they were actually engaged in thinking. I found it interesting.

> This issue of metacognition- there is no doubt about it [i.e., that it is something valuable we learnt in the course,] because we usually don't engage in it, no, there is no doubt about it. The concept [i.e. metacognition] was new for us and we never engaged in it at the same level and certainly not with our students. This was totally new for me and I plan to use it.

As is apparent from the latest two quotations, general metacognitive knowledge regarding thinking skills was seen by teachers as something with which they had not been familiar prior to the course.

> Even the skills we usually practice in class, [e.g. the scientific inquiry thinking skills, A. Z.], we are not conscious about it in the same way. We don't call them by names….

> Often we are not aware of which skill we would like [students to apply, A. Z.]. We want them to think and we… It's sitting somewhere in the back of our minds, but we ourselves are not really focused upon [saying things such as, A. Z.]… today I'm going to work on critical thinking, etc.

More supporting evidence for the fact that before the course, even teachers who applied thinking tasks in the course of instruction were doing so intuitively, without being able to conceptualize the thinking strategies they addressed on a metastrategic level, came from study 2, where several of the participants were followed in an extensive way. The case of Yael illuminates this issue (Zohar 2006).

Yael is a woman who has been teaching science in a junior high school for 17 years. In the early interview, Yael stated that one of her professional goals was to teach her students to think. However, beyond this very general statement, she was unable to answer any of the more specific questions that referred to teaching higher-order thinking. She could not describe the means by which she was engaging her students in learning to think, and when asked which thinking skills she was addressing in her teaching, Yael answered that she did not know of any thinking skills:

> I don't know which thinking skills exist, so I can't tell you. I am doing many things by intuition but I don't know how to explain what I am doing by using specific concepts.

The early classroom observation in which Yael was asked to invite the researcher to attend a "thinking" lesson confirmed that during her actual teaching, Yael indeed required her students to think in an active way. The classroom observation confirmed, however, that at this early stage, Yael lacked appropriate conceptual tools for thinking and for speaking about thinking skills. The observed lesson took place in a seventh grade classroom. The teacher seemed to be charismatic, creating an atmosphere of an intellectual challenge in the classroom. Students working in small groups competed with each other as to which group will be the first to solve a problem posed by the teacher and seemed to be highly involved with the task, which they eventually solved correctly. However, it was apparent that in leading her students through the task, the teacher used a wrong "thinking" terminology. Following the lesson, when the interviewer asked Yael why she thought this lesson was an example of a "thinking lesson," she could not give a clear answer.

In sum, the data show that before the teachers' course, Yael indeed initiated "thinking" activities in her classroom, but she did so intuitively while lacking the metastrategic knowledge that pertains to the thinking activities she had initiated. Taken together, the data from the two studies indicate that before the course, even science teachers who often applied higher-order thinking strategies in their classrooms did so "intuitively," lacking the metalevel general knowledge regarding the thinking strategies they were using. Therefore, they were unable to plan the teaching of thinking strategies in a conscious and systematic way and to address MSK in the classroom in an explicit way.

Developments in Teachers' MSK Following the Course

The data collected as part of study 2 showed that considerable developments took place following the teachers' workshop. Evidence for this claim is based on case analyses of selected teachers as well as on an analysis of the data from classroom observations and interviews of the 14 teachers as a group. For instance, during the first phase of the teachers' course, Yael was deeply impressed by what she had learned in the context of metacognition. After the first three concentrated days of the teachers' course in which she participated, she initiated the following conversation with one of the course's leaders:

> I feel that I am in a state of shock right now. According to my current understanding metacognition is the highlight of the program… I had never applied it in my work, so I'm shocked because I thought I was doing it right…. It's a real revolution in the way you ought to teach ….. I can't afford to start applying it slowly, in a gradual way, so I am already thinking about how I ought to change the way I teach the next subject I am going to work on….

A careful analysis of Yael's teaching following the course's first phase shows that she started to experiment with teaching for thinking in a more focused and explicit way than prior to the course. Throughout her work, she began to apply correct metastrategic knowledge of thinking skills in her teaching, which reflects the first steps in the emergence of pedagogical knowledge that pertain to the teaching of MSK. At a discussion that took place in the closing session of the second phase of the course, Yael expressed the following view regarding the effects of her own change process upon her students:

> When I plan my lessons I devote a greater part of my thinking to developing students' thinking. I am trying to insert a thinking section in almost every lesson, even if sometimes it is only a small section…. Following the course I became more conscious of the thinking components in my lessons. The funny thing is that my students also begin to feel some sort of change… They now know how to identify the thinking components in my lessons.

In the late classroom observation that took place at the end of the school year, Yael engaged her students in a learning activity about hormones. An analysis of this lesson showed that Yael made an enormous progress on many dimensions that pertain to teaching thinking in comparison to the early classroom observation. In contrast to the beginning of the year, Yael used a very precise thinking vocabulary to describe the thinking processes that were addressed in the late lesson. She used words such as define, compare, confirm, and conclude in a correct and precise way, indicating that she was conscious of the thinking skills that she required her students to use. She also used metastrategic knowledge as an explicit means for helping students who had difficulties with the thinking activity. In the concluding interview, Yael discusses several thinking skills in an explicit and correct way. Finally, Yael's progress at the end of the year is reflected by her strive for long-term planning and methodological teaching of thinking skills. In the late interview, she concludes by saying the following:

> I know that I used to do a lot of these things intuitively, without knowing the titles or the names. It's clear to me that now, when I know the titles – i.e., the metacognition you had taught us – I find it much easier to do it in a conscious way. I want to organize our whole science team and tell them we need to sit down [in order to plan the curriculum].

In sum, the data show that by the end of the school year, Yael had a sound metastrategic knowledge of the thinking skills she had addressed in her teaching. She also had an appropriate pedagogical knowledge that enabled her to engage her students in metastrategic thinking. She explicitly discussed elements of metastrategic knowledge with her students, using various pedagogical means. Finally, she was beginning to think about how she could use the metastrategic knowledge she had acquired for long-term and methodological planning of her teaching and for considering students' thinking difficulties. She summarized the change she went through in her own words by saying:

….Developing students' thinking is now at a higher level of awareness. I have internalized it.

The finding regarding the development in teachers' knowledge that took place during the course was corroborated by the comparison between the findings from the early and late classroom observations and interviews of the 14 teachers who participated in this part of the study. The most striking finding in this context that emerged from the classrooms observations indicated a significant development in teachers' use of the "language of thinking," concerning both the total number of "thinking" words that teachers pronounced in their lessons and the variety of different "thinking" words they had used. In the early observations, the mean number of "thinking" words that teachers pronounced in their lessons was 50.3 (SD = 31.6). In the late classroom observations, the mean number of "thinking" words increased to 77.7 (SD = 34.1). This difference was statistically significant ($t = 2.66$; $P < 0.05$) with a large effect size (ES = 0.8). The analysis that we carried out for the variety of thinking words showed that the mean number of different "thinking" words increased from 14.1 (SD = 3.65) in the early observations to 20.2 (SD = 4.52) in the late observations. This difference was also statistically significant ($t = 5.61$; $P < 0.001$) with a very large effect size (ES = 1.34). Nevertheless, only 5 of the 14 teachers actually engaged their students in metastrategic thinking during the lesson we observed.

The findings from the early and late interviews also showed a vast development in teachers' knowledge. In the interviews that followed the classroom observations, teachers were asked to explain which thinking skills they addressed during the lesson. Their replies were then verified against the classroom observation data. The results show that prior to the course, only four teachers were aware of the thinking skills addressed in the observed lesson. However, following the course (i.e., in the late interviews), 12 teachers were aware of the thinking skills addressed in their lesson. It may thus be concluded that the course helped teachers to develop the ability to correctly identify the thinking skills they addressed in their lessons.

Summary and Conclusions

This chapter examined various aspects pertaining to the teaching of thinking strategies as explicit, general structures. This means not only engaging students in activities that require them to think (see level 2 in Fig. 9.1) but also supporting them in developing explicit metaknowledge about the thinking strategies they apply in science classrooms

(see level 3 in Fig. 9.1). The pedagogies applied in this process consisted of explicit instruction of MSK that was mediated by verbal discussion, combined with multiple opportunities to practice the thinking strategies across time, coupled with individual teacher–student interaction. The part of the chapter that examines the effects of instruction reports findings from three separate studies that corroborated each other: The first study took place in "sterile" laboratory conditions, examining the teaching of the control-of-variables strategy (COV). The second study broadened the applicability of the findings from study 1 by exploring authentic classroom conditions with the COV thinking strategy. Finally, the third study further broadened the examination of authentic classroom conditions by addressing two additional thinking strategies (DRQ and FRH). The findings from all three studies were similar: The explicit teaching of MSK had dramatic effects on the development of students' strategic and metastrategic thinking. The effect of the treatment was preserved in delayed transfer tests. Another important finding was that the explicit teaching of MSK had a particularly strong effect on low-achieving students. This teaching method can therefore be offered to teachers as a practical means for supporting the development of thinking for students in general and for LA students in particular.

The final part of the chapter was devoted to issues pertaining to teachers' knowledge and professional development. The findings from the two studies about teachers' knowledge confirm that teachers' initial metastrategic knowledge is lacking and is unsatisfactory for sound teaching of higher-order thinking skills. The studies showed that metacognition for teaching thinking in general and MSK in particular was a new body of knowledge that most teachers encountered during the course for the first time. Following the course, most teachers showed a considerable development in their MSK as compared to the beginning of the course. Before the course, only a minority of the teachers were aware of the thinking strategies they had been addressing in their classrooms, and most teachers were unable to name these thinking strategies correctly. As opposed to that, by the end of the course, most teachers were aware of the thinking strategies they had been addressing in their classroom and were able to name most or all of these strategies correctly. By the end of the course, teachers improved their use of the language of thinking as compared with the beginning of the course. In addition, by the end of the course, considerable developments were observed in teachers' pedagogical knowledge in the context of teaching metacognition. However, only about one third of the teachers were able to engage their students in metacognitive activities that foster students' MSK.

These findings show that a professional development course can indeed help teachers make considerable progress with respect to the knowledge that is required for applying MSK in the classroom. In particular, the course was helpful in helping teachers address thinking strategies as explicit educational goals rather than teach them "intuitively." This is significant because it enables teachers to plan the teaching of thinking strategies in a systematic manner rather than address thinking as a by-product of other learning goals addressed during teaching. It seems that in order to help the majority of teachers to be able to actually apply the teaching of MSK in their classrooms, future PD programs will require even more support than what was given in the course described here.

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Chapter 10
A Metacognitive Teaching Strategy for Preservice Teachers: Collaborative Diagnosis of Conceptual Understanding in Science

Osnat Eldar, Bat-Sheva Eylon, and Miky Ronen

Introduction

Instructional courses for preservice teachers are usually separated into disciplinary content courses and pedagogical courses. The separate teaching of content and pedagogy is problematic since it does not support the integration of subject matter knowledge and pedagogy required for developing pedagogical content knowledge (PCK) (Shulman 1986, 1987, 1990). This fragmentation of teachers' learning experiences leaves individual teachers the challenge of developing pedagogical content knowledge on their own during their practice as teachers (Ball 2000). However, it is not clear that the desired development of PCK by learning in and from practice (Ball and Cohen 1999) occurs naturally in the course of time. Yet, this knowledge is fundamental to the core tasks of teaching and is critical for developing the ability to teach well. Sabar (1994) suggests that special frameworks must be constructed to help the preservice teachers carry out this integration.

This chapter describes the design of a preservice science course which attempts to promote the attainment of both disciplinary knowledge and pedagogical content knowledge by using metacognitive teaching strategies. The study investigates how the use of these strategies contributes to the learning of content and pedagogy. The study was carried out in the context of a geometrical optics course for preservice teachers.

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What are important learning goals (content and pedagogy) for preservice teachers? What challenges do they present to teacher educators? Why is it important to use metacognitive teaching strategies to achieve these goals?

Concerning knowledge in the scientific domain, a central goal for preservice teachers as for other learners is to develop sound conceptual understanding and the ability to apply their newly acquired knowledge in solving problems. Research suggests that the attainment of these goals with learners of all levels is very challenging. Numerous studies document the fact that students' prior knowledge in science, as well as the knowledge developed in the course of studying science, involves conceptions that are incongruent with normative science. These conceptions are resistant to change (Eylon and Linn 1988; Pfundt and Duit 1994). Since preservice teachers have scientific conceptions similar to those of school students (Galili and Hazan 2000), teaching for conceptual understanding in preservice courses faces similar challenges.

A common feature of teaching strategies that promote the acquisition of conceptual understanding is students' "active engagement" (minds on). For example, Hake (1998) conducted a meta-study on introductory physics courses and used the Force Concept Inventory (FCI) developed by Hestenes et al. (1992) to evaluate students' conceptual understanding in the end of the courses. Hake found a significant difference between students who studied in courses using transmissionist teaching strategies and those that emphasized students' active engagement. Another common feature of teaching strategies that promote understanding and problem-solving is the use of metacognition and an explicit requirement to reflect on learning. There is consensus among researchers that metacognitive processes promote cognitive abilities and that metacognition is important for promoting learning processes (Brown 1994). Examples can be found in fields such as reading comprehension (Veenman and Beishuizen 2004), mathematical problem-solving (Kramarski and Mevarech 2003), and science teaching (Zion et al. 2005; Zohar 1999). Research shows that learning outcomes are improved when more metacognitive processes accrue (Lambert 2000) and that high-achieving learners apply more metacognitive processes than low-achieving learners (Rimor 2002).

Concerning pedagogy, an important goal is to model to preservice teachers effective teaching strategies that they will be able to use with their students. In addition, the teachers should be able to identify the critical characteristics of these strategies and also learn how to use them. Without modeling to the preservice teachers teaching approaches that are effective in attaining goals such as teaching for understanding in the context of a content course, it is very unlikely that the preservice teachers will be able to come up with such strategies on their own. In this chapter we question the common assumption that "teachers teach the way they were taught." The implicit experiencing of the teaching and learning strategies in the context of a disciplinary course may not be sufficient for constructing the desired pedagogical content knowledge. Special metacognitive scaffolding may be needed to identify and explicate the knowledge.

The design of the preservice course in the present study attempted to promote the above mentioned content and pedagogy goals by attending to the challenges that

were mentioned earlier. The course employed a metacognitive instructional strategy *collaborative diagnosis of conceptions* (CDC), accompanied by continuous and explicit discussions about the content and pedagogical characteristics of the learning that took place. In the CDC strategy the preservice teachers carry out an activity individually, examine the answers collaboratively with peers, compare and contrast the answers, and attempt to come up with a consensual answer. Later in the course they try to identify conceptions that underlie various answers (their own and hypothetical students' answers) and are asked to come up with suggested activities to advance students' understanding. The strategy emphasizes the social aspect of learning, specifically referring to the influence of social interaction on the knowledge construction of the learner (Vygotsky 1978). The assumption is that learning is a social process, and in collaborative learning, knowledge is constructed through negotiation and discussion. In particular, research shows that the socially shared metacognition is especially effective in learning how to solve problems in groups, a focus of the CDC strategy. For example, Hurme et al. (2009), who investigated socially shared metacognition of preservice primary teachers in a computer-supported mathematics course, found that although initially the preservice teachers felt that the collaborative tasks were difficult, this feeling decreased when socially shared metacognition emerged. Consequently, learning increased.

The goal of the present study was to test whether, in the context of the disciplinary course which employed the strategies described earlier, the preservice teachers would develop their conceptual understanding as well as their pedagogical content knowledge. Another goal was to study the role of metacognition in the process of learning and to determine what scaffolding is needed to help preservice teachers integrate the content and pedagogical aspects of learning.

Pedagogical Content Knowledge

According to Shulman (1986, 1987), teachers' professional knowledge should involve several components, one of which is pedagogical content knowledge (PCK). Shulman describes PCK as "the most powerful analogies, illustrations, examples, explanations, and demonstrations….., the ways of representing and formulating the subject that makes it comprehensible for others" (1986, p. 9). He claims that this component characterizes the special knowledge acquired by teachers in their subject domains. Good teachers possess a strong PCK knowledge. Moreover, this knowledge is essential for designing curricula that enable students to construct a sound understanding of the domain knowledge. Shulman's view of teachers' knowledge led to a shift in understanding teachers' work by focusing not only on their behavior but also on their knowledge.

Although PCK is a notion commonly used by scholars, the main challenge is how to capture teachers' PCK, since teachers are often unaware of the knowledge they possess. Moreover, in their regular practice they do not need to explicate it. PCK is content dependent and is difficult to conceptualize for different subjects.

Its boundaries are blurry and it is not uniquely defined in the literature. Some researchers, however (e.g., Loughran et al. 2004), claim that teachers' PCK is recognizable in their approach to teaching specific content.

For our purposes, we will refer to the framework proposed by Magnusson et al. (1999) for conceptualizing PCK for science teaching. They described PCK as consisting of five components: (a) orientation toward science teaching, (b) knowledge and beliefs about the science curriculum, (c) knowledge and beliefs about students' understanding of specific science topics, (d) knowledge and beliefs about assessment in science, and (e) knowledge and beliefs about instructional strategies for teaching science. In this chapter we focus on the third and fifth components dealing with knowledge and beliefs about students' understanding of specific science topics and about instructional strategies for teaching science. According to Magnusson et al. (1999), each of these components consists of several categories: (a) knowledge of students' understanding of science which includes the requirement of learning specific science concepts, and the areas of science that students find difficult, and (b) knowledge of instructional strategies includes knowledge of subject-specific strategies and knowledge of topic-specific strategies involving different representations and activities.

Definitions of Metacognition

Metacognition was formerly referred to as knowledge about and regulation of one's cognitive activities in learning processes (Brown 1977; Flavell 1979). Flavell defined the concept as follows: "Metacognition refers to one's knowledge concerning one's own cognitive processes and products or anything related to them,…." and "Metacognition refers among other things, to the active monitoring and consequent regulation and orchestration of these processes in relation to the cognitive objects or data on which they bear, usually in the service of some concrete goal or objective" (Flavell 1976) (p. 232). Brown included in her definition the central distinction that metacognition refers to learners' understanding of their knowledge; an understanding that can be reflected in effective use of that knowledge and good performance on academic tasks (Brown 1977). Schraw and Moshman (1995) refer to the same basic distinction between *metacognitive knowledge* (i.e., what one knows about cognition) and *metacognitive control processes* (i.e., how one uses that knowledge to regulate cognition). They categorize metacognitive knowledge into three kinds of metacognitive awareness: declarative knowledge, procedural knowledge, and conditional knowledge. Metacognitive control processes involve the active monitoring and regulation of cognitive processes. Such processes are central to planning, problem-solving, evaluating, and many aspects of learning.

One of the components of metacognitive knowledge is metastrategic knowledge that refers to explicit knowledge regarding the thinking about strategies being used during instruction. Findings from several studies show that the metastrategic knowledge of teachers is insufficient for sound teaching of higher-order teaching skills (Zohar 2006). Zohar and collaborators (Zohar and Peled 2008;

Zohar and Ben David 2008) have shown, however, that this knowledge can be improved by explicit instruction and that such knowledge can affect students' cognitive and metacognitive thinking.

More recently, Veenman and Van Hout-Wolters (2006) summarized several of the terms we commonly associate with metacognition, including metacognitive beliefs, metacognitive awareness, metacognitive experiences, metacognitive knowledge, a feeling of knowing, judgment of learning, theory of mind, metamemory, metacognitive skills, executive skills, higher-order skills, metacomponents, monitoring comprehension, learning strategies, heuristic strategies, and self-regulation. This long list of terms underscores the importance of specifying what view of metacognition is being taken in a particular study. In the next section we describe how we used metacognition in this research.

Metacognition in This Research

Since the construct of metacognition is not unequivocally defined, its characterization in this research is based on two different sources: (1) choice of relevant aspects from several definitions from the literature (top-down) and (2) categories emerging from analysis of class discourse and the learners' reflection after a CDC lesson (bottom-up).

Most of the definitions presented in the previous section make a clear distinction between metacognitive knowledge and the metacognitive regulation or control processes. We follow this distinction. Figure 10.1 presents the framework that was used in this research to characterize the CDC tasks, the learners' performances, their discourse, and their reflections. In the present study we focus mainly on metacognitive knowledge, and therefore we elaborate on its various components. Following the literature and our own focus, we identify four central categories (see Table 10.1). In category B1, *knowledge about people*, we underscore both the understanding of one's own thought processes (B1_1) and the thought processes of others (B1_2). This aspect is very central in the CDC strategy, which is a collaborative strategy that aims to promote preservice teachers' knowledge about alternative ways of thinking and in particular how to understand their students. Category B2, *metastrategic knowledge*, is also central in our study since it plays an important role in the development of the teachers' conceptual knowledge as well as their understanding of the CDC strategy and the actions involved in carrying out its various steps. In the section "CDC in Action" we provide an example of the important role of metastrategic knowledge. The third category, B3, *knowledge about tasks*, is a central component in teachers' pedagogical content knowledge. The teachers need to understand how the specific optics tasks that they study are structured and how they promote learning. This understanding will enable them to design learning experiences for their students. The fourth category, B4, *knowledge about knowledge integration*, involves knowledge about two aspects concerning knowledge integration. One aspect, B4_1, is concerned with understanding

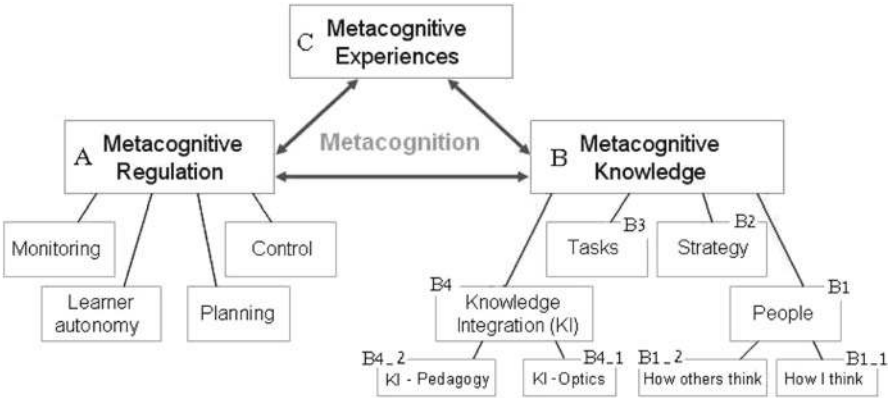


Fig. 10.1 Metacognition categories in this research

Table 10.1 The metacognitive categories in the context of this study

The category	Description (in the context of this study)
A: Metacognitive regulation	
	Capabilities involved in regulating actions (monitoring, planning, and control) and in independent learning
B: Metacognitive knowledge	
B1: Knowledge about people	**Knowledge about thought processes**
B1_1: How I think	Understanding my thought processes
B1_2: How others think	Understanding the thought processes of others
B2: Knowledge about strategy (metastrategic knowledge)	**Knowledge about the structure of an instructional strategy and how it promotes learning**
B3: Knowledge about tasks	**Understanding the structure of tasks and how they promote learning**
B4: Knowledge about knowledge integration (KI)	
B4_1: Knowledge about KI in optics	Understanding the structure of concepts and principles in optics and how they relate to alternative (normative and nonnormative) ways of relating the concepts and the principles
B4_2: Knowledge about pedagogy related to KI	Understanding how general pedagogical knowledge (PK) can be applied in the context of teaching optics to respond dynamically to students' normative and nonnormative scientific ideas (PCK)
C: Metacognitive experiences	

relationships between alternative ways (normative and nonnormative) of structuring the concepts and relationships in optics and how a given structure affects the way learners solve problems in this domain. This type of knowledge plays a central role in the preservice teachers' ability to identify the sources of various patterns of student solutions and to design instruction that responds to students' ideas. For example, if a learner's knowledge structure does *not* relate the act of "seeing" to

rays emitted from an object (or scattered from it) and to the interaction of these rays with the eye ("entering the eye"), this has consequences for the way the student solves a range of problems about field of sight. The other aspect of this category, B4_2, is concerned with the ways to respond dynamically to students' scientific ideas (normative and nonnormative) in a manner that takes into account the students' knowledge structures and leads them to reconsider their ideas. As described above, the CDC strategy provides learning opportunities to the preservice teachers for developing their metacognitive knowledge. But at the same time the enactment of this strategy requires the learners to monitor, plan, and control the actions involved in interacting with peers and resources. For example, when there is disagreement between members of the group, they have to make decisions when to seek additional information from external resources such as experiments, computer simulation, or the teacher, and what resource to use for the particular situation. Hence the learners have opportunities to develop also metacognitive regulation (category A). As depicted in Fig. 10.1, there is a mutual relationship between metacognitive regulation and metacognitive knowledge; as in the former example, understanding how others think (category B1_2) influences the plan for deciding about the effective resource to resolve the conflict.

The CDC Strategy

The CDC strategy was developed to enable preservice teachers to learn the subject matter of a particular topic in physics and to reflect on thinking, learning, and teaching. In the present research the physics topic was geometrical optics. The CDC strategy aims to develop the preservice teachers' deep understanding of content by helping them to identify their prior conceptions and to link their new knowledge in optics to their previous knowledge. This strategy addresses diSessa's claim about fragmentation in learners' knowledge (diSessa 1988) and is aimed to promote knowledge integration (Linn and Eylon 2006, 2011). At the same time the CDC strategy also aims to develop pedagogical content knowledge. It aims to enhance one of the important skills of teaching: the ability to follow closely the students' conceptual understanding and to respond accordingly with appropriate instruction. This focus enables the preservice teachers to develop their pedagogical content knowledge (PCK) about ways to interact in the future with their students using a similar instructional strategy. The learning process was supported by a web-based collaborative environment (Ronen et al. 2006) that helps in constructing the collaborative learning. During the course the preservice teachers did not meet students, but they were exposed to students' work and to students' answers to the assignments that they did during the course.

The CDC strategy can be characterized along two dimensions. One dimension involves the act of diagnosis (see section "The Diagnosis Dimension"), and the other dimension describes aspects of collaboration involved in carrying out the strategy (see section "The Collaboration Dimension").

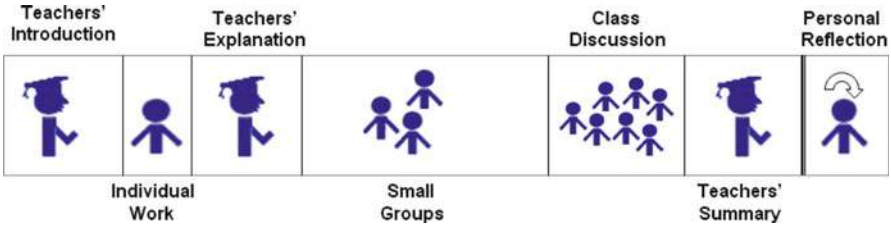


Fig. 10.2 Structure of a typical lesson

CDC in Action

The CDC activity is part of a lesson. Figure 10.2 shows the structure of a typical lesson including a CDC activity. The course involved five cycles of implementing the CDC strategy: in lessons 1, 5, 7, 10, and in the final test which took place after the last meeting. The implementations started with partial application of the various elements of the CDC strategy and evolved toward a full implementation toward the end of the course.

To be more concrete, Fig. 10.3 shows an example of a CDC activity that was carried out in the middle stages of the course. As shown in the figure, the steps of the activity can be represented on a two-dimensional matrix characterizing the diagnosis and collaborative aspects of each step. The arrows present the sequence of actions in the particular example. The figure also shows the concrete activity. The CDC activity usually culminates in a class discussion aimed at exposing all the learners to the groups' conclusions, and at building a common knowledge base that includes both the subject matter and pedagogical aspects.

The Diagnosis Dimension

The diagnosis dimension consists of five elements, most of which provide opportunities for promoting metacognitive thinking (see Fig. 10.3 for an example):

1. *Create an artifact*: This element of the activity is carried out individually and is aimed at eliciting learners' prior conceptions. The learners are asked to represent their thoughts about a scientific phenomenon usually involving a visual representation. This artifact will be used later in the strategy as a tool for explaining their thoughts. Although this element by itself is not metacognitive, it is important for creating the setting that will help metacognitive thinking in the other elements.
2. *Compare and contrast artifacts*: The learners are asked to find the differences between their individual artifacts. This activity encourages the learners to address their own thinking and to compare it to that of their peers (category B1 in Fig. 10.1). Through this process the learners recognize the essential features of their own representation and learn about other representations. As a result,

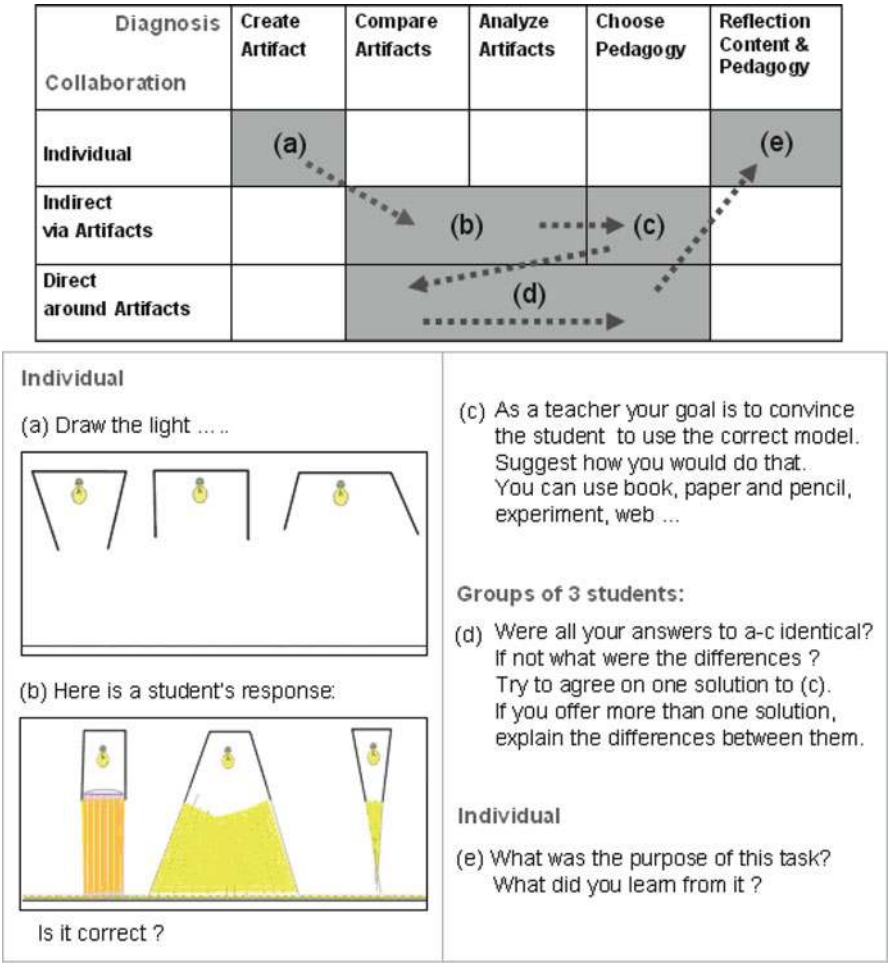


Fig. 10.3 An example of a CDC activity

they can deepen their understanding and possibly even change it with the help of their peers.

3. *Analyze artifacts*: The learners are asked to evaluate the scientific validity of the artifacts, the source of conceptions leading to the formation of the different artifacts, possibly reaching a consensus about the "best" artifact. To carry out this process, the learners have to acquire metacognitive knowledge about the ways their peers think about scientific phenomena and how they are applied in concrete cases. The learners also have to identify normative and nonnormative scientific ways of thinking about the optical phenomena and to conjecture what are the sources of their own ideas and the ideas of others. In this stage, the preservice teachers learn about the scientific knowledge, how this knowledge is built, and

how alternative conceptions come about. By the end of this stage they decide what conception is better and why (categories B1and B4 in Fig. 10.1).
4. *Choose a pedagogical strategy*: The learners are asked to choose, on the basis of their diagnosis, a pedagogical strategy for helping students promote their conceptual understanding. To carry out this step, the learners need knowledge about tasks (B3) and about knowledge integration both in optics and in pedagogy (B4). The learners have to connect the knowledge they acquired in the previous stage about how others think to the pedagogical knowledge on how they can change this way of thinking. During the process they have to explicate their pedagogical metastrategic knowledge and explain their decisions to their peers (categories B1 and B4 in Fig. 10.1).
5. *Reflect on content and pedagogy*: The learners are asked to reflect on the activity from two points of view: The first is about the content they have learned, and the second involves the pedagogy characterizing the teaching and learning strategies. In the reflection they have to explicate what they have learned (categories B1, B2, B3, and B4 in Fig. 10.1).

The Collaboration Dimension

The CDC strategy involves three levels of collaborative work:

1. *Individual work*: The learners carry out an activity by themselves.
2. *Indirect collaboration via artifacts*: The learners can work on artifacts created by others.
3. *Direct collaboration around artifacts*: The learners work collaboratively around artifacts on one or more of the various aspects of diagnosis (e.g., comparing and contrasting their artifacts).

The Study

The Research Goals and Questions

This study aimed at investigating the impact of the CDC strategy on the preservice teachers' content knowledge, in particular, learners' conceptual understanding after completing the course, their ability to apply the knowledge, and their diagnostic skills (research question 1 below). Since the CDC is a metacognitive instructional strategy which involves diagnosis of conceptions (see section "The CDC Strategy"), we expected it to enhance the attainment of the above mentioned learning outcomes.

Another goal of the study was to study the acquisition of pedagogical content knowledge by the preservice teachers. In particular, we were interested to investigate

whether teachers would be able to characterize the instructional approach that they experienced, since one of the central considerations in designing the CDC strategy was to model a strategy they would be able to use in the future. Following a pilot study which showed that many of the preservice teachers were unable to provide a reasonable characterization of the instructional approach (see "Results" below), activities of structured reflection were added to the course. Thus another goal of the present study was to investigate whether this metacognitive scaffolding promoted the teachers' PCK (research question 2 below).

An additional issue that concerned us was the role of metacognition in the learning process (research question 3 below).

Accordingly, the following questions were studied:

1. What were, after completing the course, the preservice teachers' achievements in the conceptual, application, and diagnostic questions in the posttest?
2. How well could the teachers explicate the characteristics of the course after completing it? How did the addition of structured reflection on pedagogy influence this aspect of the preservice teachers' PCK?
3. What was the role of metacognition in the process of learning with the CDC strategy?

Methodology

The study was carried out in the context of a preservice geometrical optics course for elementary school teachers given in an academic college of education in Israel. It is one of the basic science courses for preservice science teachers in a 4-year B. Ed. program. The length of the course was 28 academic hours, 2 h each week. This course was implemented in two different versions, A and B, that differed in the way in which they integrated the CDC strategy into the teaching of the course.

Sample

The preservice teachers who participated in the study were divided into two groups: Group A ($n=16$) studied the first version of the course, and group B ($n=19$) studied the second version. Following the study of version B, additional five groups of preservice teachers ($n=70$) studied with this version.

In order to compare the composition of groups A and B, we located the scores of the students in groups A and B in two science courses studied prior to the course that is the focus of the present study. The comparison indicated that the groups were similar in their average scores in these tests, but group B was more heterogeneous than group A. Further support to this conclusion was given by the physics teachers who taught these courses who claimed that the groups were similar in composition and ability.

The Versions of the Course

In the two versions of the course, the students carried out several times collaborative diagnosis of conceptions (CDC) activities that were followed by reflection on the content. As described above, the CDC strategy supports metacognition on the learning of content by exposing the learners to different conceptions and by giving them an opportunity to discuss and reconsider their ideas. The implementation of the strategy in this regard was similar in the two versions of the course, but the versions differed in the amount of metacognitive scaffolding of the pedagogical aspects of learning. The *first version, A*, involved only a general discussion of the pedagogical implications of the approach. In the *second version, B*, each lesson, in particular, a lesson involving the CDC strategy, was followed by structured reflection on the pedagogy and content that were studied in the particular lesson. For example, one of the strategies involved habitual reporting and discussion of learning that occurred in the conceptual and the pedagogical areas. The learners were asked to answer two questions at the end of each lesson: What have you learned about optics during the lesson? What have you learned about teaching optics? The collaborative work was facilitated by a computer-based environment allowing students to test their ideas and to compare them to their classmates' ideas. Class discussion was added, which helped in exposing the learners to the conclusions from the work of different groups and in building a common knowledge base.

Research Tools and Analysis for Questions 1 and 2

After completing the course, all teachers were given a posttest and a questionnaire to assess their achievements in optics and their pedagogical content knowledge (PCK).

The Posttest

The test included three types of questions: five questions testing conceptual understanding, five questions testing application of optics knowledge, and one question testing the diagnostic capability of the preservice teachers. The reliability of the test is $\alpha_{\text{Cronbach}} = 0.78$. Figures 10.4–10.6 present examples of each question type. The conceptual question in Fig. 10.4 requires both a visual representation and a verbal explanation and can expose common conceptions of learners. In many courses students are not required to answer such conceptual questions. Also the diagnostic question in Fig. 10.6 is not a standard question. In addition to testing content directly, this question tests to what extent the preservice teachers can uncover the conceptions underlying the different answers and also tests the teachers' ability to suggest remedies, both important elements of PCK. The application question exemplified in Fig. 10.5 is a standard application question in geometrical optics courses.

A rubric for analyzing the answers was developed and validated by five physics educators. All tests were graded by two physics teachers.

The drawing describes a man observing a light bulb. Complete the drawing in a way that will explain how the man sees the light bulb.

A man observing a bug in a room lit by an electric bulb.
Complete the drawing in a way that will explain how the man sees the bug.

Fig. 10.4 Examples of conceptual questions

O is a light source and M a spherical mirror. The diagram shows two rays reflected by the mirror.

a) What type of mirror is M?
b) Add arrows that indicate the direction of light propagation.
c) Where is the image of O formed?
d) Is the image real or virtual?
e) Add two more rays emerging from O and reflected by the mirror.

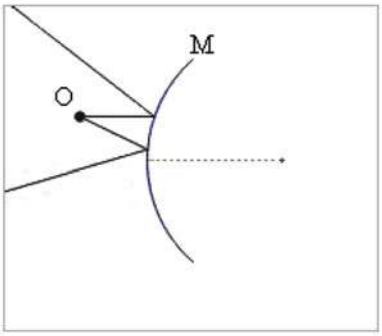
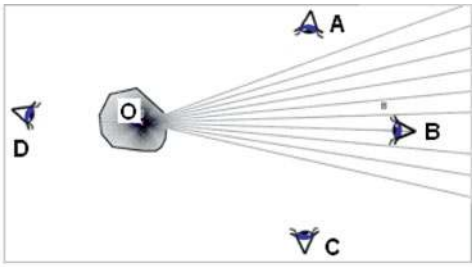


Fig. 10.5 An example for an application question

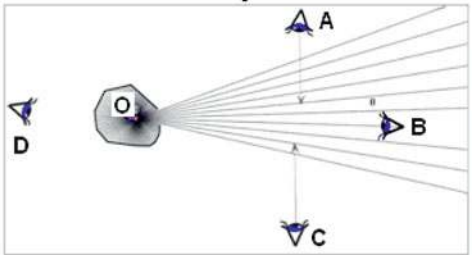
O is a point light source partially surrounded by an opaque barrier.

a) Which of the eyes (A-D) will be able to see the light source? Explain.



A student's answer was: A, B and C.
The student's explanation is presented:

Student's explanation



b) Is his answer correct?
c) What is the student's conceptual model ?
d) As a teacher your mission is to change the student's approach. You can use any aids: book, computer simulation, experiment...

Fig. 10.6 An example for a diagnostic question

The Pedagogical Questionnaire

The questionnaire examined the teachers' ability to characterize the instructional strategy and its utility for learning and teaching.

The questionnaire included four open questions:

1. What methods were used in the course?
2. In what ways did these methods help you learn optics?
3. In what ways did the course help you as a preservice teacher?
4. What do you think a teacher should do to promote conceptual understanding of students in the domain of optical geometry?

The analysis of the answers was carried out as follows:

1. The research team predefined the following characteristics of the instructional strategy: individual work, group work, teacher summary, exposure to knowledge, identifying conceptions, comparing with peers, discussions, persuasion.
2. The answers of all the students in groups A and B were categorized according to these characteristics.
3. For each student, the percentage of predefined characteristics that he/she mentioned was calculated. This percentage constituted the pedagogy score reported in the results.

Research Tools and Analysis for Question 3

Since the CDC is a metacognitive strategy, we expected it to lead to metacognitive discussions during the CDC activity and in the reflections after the CDC lesson. Consequently, all the discussions among the students during the CDC activities were audio and video recorded and transcribed. In addition, all the artifacts created during these discussions as well as students' reflections after the CDC lessons were collected.

Analysis of the Transcripts

1. The transcripts were divided into episodes, each characterized by a different theme.
2. Each episode was divided into turns, each characterized by a specific speaker.
3. The discourse of the participants (learners and teacher) inside an episode was described by who is the speaker, who is active regarding the response, what is the interaction, what is the content of the discourse (scientific concepts, pedagogical issues, metacognitive phrases), how do the learners convince each other, and what are the metacognitive elements in the learner's discourse.

Analysis of Learners' Reflections

We identified the metacognitive elements in the learners' reflections after a CDC lesson and related them to the definition of metacognition in this study (Fig. 10.1).

Results

Research Question 1: Content Knowledge

Overall, the preservice teachers in group A that studied the CDC strategy only (without additional structured reflection) performed well on the posttest (average = 89.0, SD = 7.2). As indicated in Table 10.2, they had high scores on the conceptual and diagnostic questions and relatively lower scores in the application questions. A similar pattern was found in group B that received structured reflection in addition to the CDC and in five additional groups ($n_{total} = 70$) that studied with version B (not reported here in detail). These findings are not surprising since the CDC strategy focuses on advancing conceptual understanding and developing diagnostic skills. The relatively lower scores in the application questions can be explained by the fact that the total time of the course was not changed, and less time was spent on practicing standard application tasks. Although we did not carry out a systematic comparison with previous courses, according to the instructors of this course, the average performance of the students on the application questions in the present study was very similar to that of students in previous disciplinary courses in the same topic that did not use the CDC strategy. The level of conceptual understanding was, however, much higher in the new course.

Research Question 2: Pedagogical Content Knowledge

Table 10.2 shows that group A had a high score (average = 91.4) in the diagnostic question that tested teachers' skill in diagnosing conceptions underlying a certain answer and in suggesting possible remedies. However, the preservice teachers in

Table 10.2 Content knowledge and pedagogical knowledge at the end of the course

	Conceptual		Application		Diagnostic		Pedagogy	
Group (N)	Mean	Mean	STD	STD	Mean	STD	Mean	STD
A (14)	94.0	83.1	13.0	6.6	91.4	5.3	32.0	15.0
B (19)	82.6	74.7	19.3	17.8	92.0	10.2	75.0	20.0
K–W[a]	$\chi^2_1 = 0.41$ (NS)		$\chi^2_1 = 1.68$ (NS)		$\chi^2_1 = 0.82$ (NS)		$\chi^2_1 = 7$ $p < 0.005$	

[a]*K–W* Kruskal–Wallis test

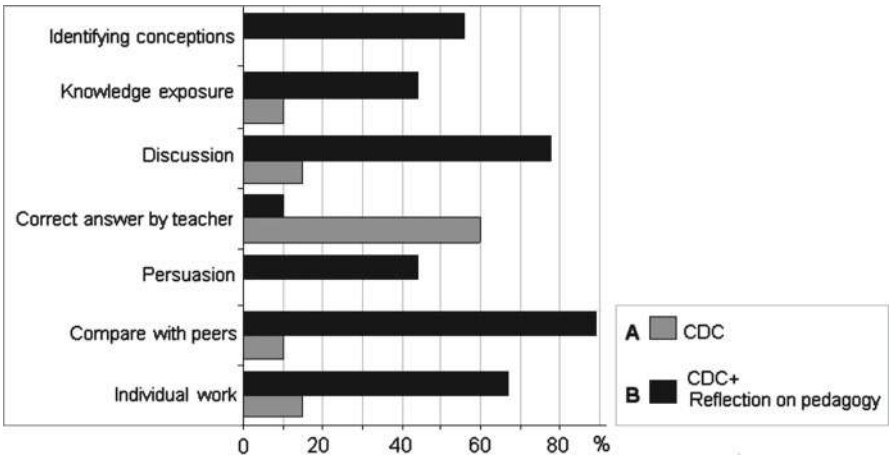


Fig. 10.7 Distribution of pedagogy categories written by the learners in groups A and B

this group were weak in characterizing the pedagogical approach (average = 32). As described above, the structured reflection in version B was added in an attempt to enhance students' performance in this aspect. The results in Table 10.2 indicate that indeed group B had much higher pedagogy scores than group A (average = 75). Thus the structured reflection was very effective in alleviating the preservice teachers' pedagogical content knowledge.

The lower pedagogy scores of learners in group A indicate that overall they identified significantly less characteristics of the instructional approach than learners in group B. Figure 10.7 presents a more detailed view of the comparative distribution of the characteristics that emerged from the categorization of the answers concerning the open question about pedagogy. It shows the percentage of learners who mentioned the various characteristics at least once. The dominant characteristic in group A was "the provision of correct answers by the teacher." This characteristic, which does not express what actually occurred in the class, was mentioned by 60% of the learners while only 10% of the learners in group B mentioned the same characteristic. In contrast, a large proportion of the learners in group B mentioned the major characteristics of the CDC strategy.

Additional support for these findings was found in the interviews: Learners in group B explicated the structure and rationale of the CDC strategy; they realized the importance of the collaborative nature of this strategy and how the strategy can help in communicating about optical phenomena. They also highlighted the fact that the strategy helped them develop the skill of persuasion based on scientific experiments.

It is reasonable to assume that the differences between groups A and B in characterizing pedagogy can be attributed to the reflection on content and pedagogy that was integrated into the CDC version of group B. Additional support for this interpretation can be found in the results presented in Fig. 10.8. This figure presents the distribution of the category "active learner," a component of the metastrategic

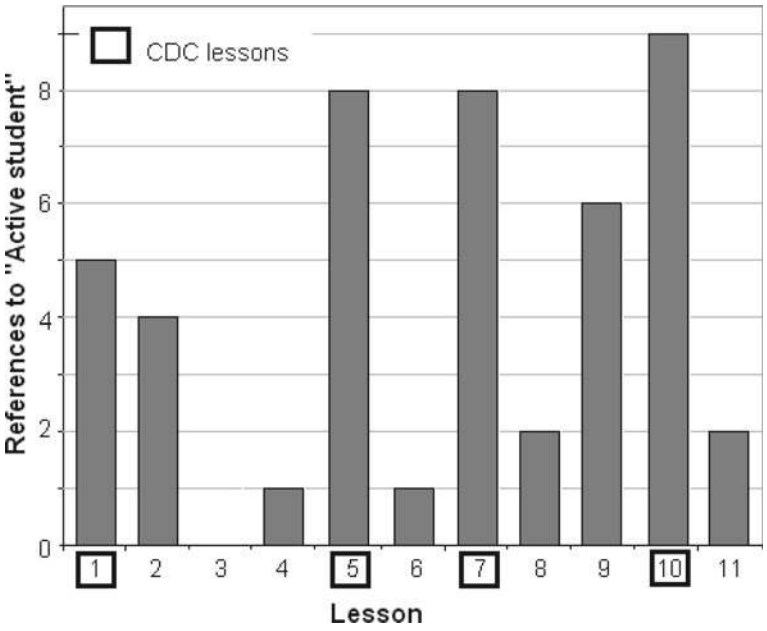


Fig. 10.8 Reference to the category "active learner" mentioned in learners' reflections during the lessons of the course

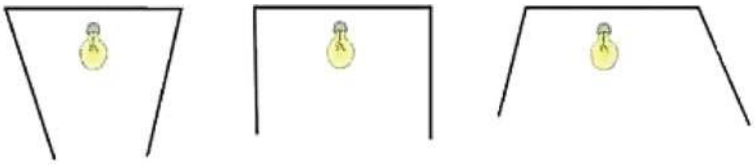
knowledge, mentioned in students' reflections. As indicated in the figure, this aspect was mentioned in most of the lessons and was most prominent in lessons involving the CDC strategy. There was an increase throughout the CDC lessons, suggesting that students developed higher sensitivity to this characteristic of the lesson. The following quote from a preservice teacher's reflection after a CDC lesson demonstrates her understanding of active learning in the CDC strategy:

"Students have to think about a phenomenon *by themselves* and only in the second stage can they contribute to a fruitful discussion, which can lead to a scientific answer."

The lessons in which the category was mentioned by fewer learners were teacher centered, involving activities such as the teachers' summary of a topic.

Research Question 3: The Role of Metacognition in Learning

In this section we examine how the learners reached the desired goals of this course and what obstacles they experienced. We carried out an extensive discourse analysis, focusing on different aspects such as the development in students' conceptual and pedagogical knowledge within a given lesson as well as throughout the course, the patterns of interaction among students, and the role of the teacher (not presented



Three light bulbs are surrounded by different lampshades.
Describe the light propagation for each case (draw and explain your drawing).

Fig. 10.9 The CDC assignment

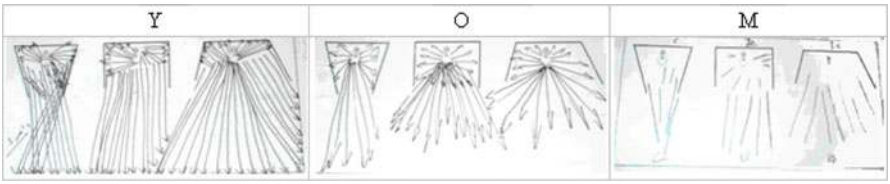


Fig. 10.10 The learners' answers in the first stage

here). We present below a case study illustrating some examples of the findings. In particular, we focus on the attainment of metastrategic knowledge.

A Case Study: Studying with the CDC Strategy

The following example describes a CDC activity involving three preservice teachers; it shows how the learners acquired metastrategic knowledge concerning the "compare and contrast" component of the CDC strategy. In the first stage, the preservice teachers worked individually on the question presented in Fig. 10.9 and drew the answers presented in Fig. 10.10.

In the second stage of the CDC strategy, the learners were asked to compare their answers. The comparison of the artifacts requires metastrategic knowledge involving two major steps: First, the learners have to characterize for each artifact the main features of the visual representations, and then they have to compare these features in the different artifacts. The relevant features are related to the basic principles of geometric optics leading to the following questions: Does the light originate from the source? Are the light rays represented by straight lines? Is the light scattered in all directions? Does the light change its direction? In comparing the answers, the preservice teachers first concluded that: "All the answers are the same: they are all correct." This result suggests that they could not identify the important features that differentiate between the answers. Table 10.3 presents the discourse that followed including (in bold) the teacher's interaction with the group (O, Oved; M, Miriam; Y, Yossi), our interpretation, and reference to the categories of metacognition in Fig. 10.1 and Table 10.1. As can be seen from the table, the teacher guided the

Table 10.3 The discourse in the "compare and contrast" CDC component in the task shown in Fig. 10.9

Speaker	Statement	Comments	Metacognitive categories
Teacher	**In the first stage you have to compare your answers**	Clarification about the task	B3
M	They are all the same	The learner does not recognize any differences	
Teacher	*Does this drawing resemble the others? Are they really the same?*	The teacher suggests to the learner to reexamine his reply	
M	It looks alike	The learner still does not recognize the differences	
Teacher	*Look here and here. Are they the same drawings?*	The teacher directs the learner's attention to specific details in the drawing	
M	No	The learner (finally) realizes the difference	
Teacher	*Since you say no, what are the differences?*	The teacher asks for clarification	
Y	*It is not the same, because the angles are different*	The learner mentions the *angle* (a relevant scientific concept)	B4
O	Here it is parallel	The learner mentions the *parallelism of rays* (a relevant scientific concept)	B4
Teacher	*OK. So here you see parallel light rays and there you don't; in what way are they similar?*	The teacher directs the learner to additional relevant comparisons and introduces more accurate scientific language	B4
Y	They are similar because they don't cross the barrier	The learner relates to the *barrier* (a relevant scientific concept)	B4
M	Also in the beginning the light stays inside the square		
M	The upper side looks the same Yes, the upper side is the same		
Teacher	*Look at this drawing – there is something different*	The teacher suggests that they focus on a certain part of the drawing	B2
Y	Yes, it is different	The learner identifies another difference	

(continued)

Table 10.3 (continued)

Speaker	Statement	Comments	Metacognitive categories
Teacher	*Why is it different?*	The teacher asks for clarification	B4
Y	Because the light is not scattered toward the upper side	The learner identifies the nature of the difference (no scattering upside)	B4
Teacher	*Yes, it is not scattered upside; what about downside?*		
Y	This is equal to this		
Teacher	*What are the differences?*		
M	They [the rays] are not parallel		B4
Teacher	*This is almost parallel; what else?*		
M	Here there are more [rays]…		
Teacher	*Here there are more rays; what else?*		
M	Here there are fewer rays.		
Teacher	*Are there additional differences?*		
M	The spacing [among the rays] here is different from the spacing there		

preservice teachers to identify the important features of the answers using several metacognitive elements. Consequently, the learners were able to differentiate between the drawings. The fact that similar difficulties to compare and contrast answers were also observed in other teams highlights the complexity of this apparently simple step in the CDC strategy. As a result of getting experience in diagnosis, in the end of the course all students knew how to carry out this step of the strategy.

The brief case study described above is characteristic of what happened in the other steps of the CDC strategy, each of which has some associated metastrategic knowledge required for its execution as well as some relevant cognitive knowledge (e.g., how to apply a certain principle in geometric optics). Since the course tries to build the learner's subject matter knowledge as well as pedagogical content knowledge, the teacher had to guide the learners in both the metacognitive and cognitive aspects.

Metacognitive Knowledge Demonstrated During the CDC Discourse

The CDC strategy includes several metacognitive elements and provides the learners with an opportunity to develop their metacognitive thinking. Do the learners make use of this opportunity? We investigated this issue by analyzing the discourse among learners who worked in small groups on the CDC activities, and the learners' reflection after a CDC activity. The following are examples from the discourse that highlight the metacognitive way of thinking demonstrated by the learners. We relate the examples to the categories of metacognition in Fig. 10.1 and Table 10.1.

In the discourse there were phrases that show elements of metacognitive thinking. The learners talked about *what they understood* as indicated in the phrase "I think what influences…." They realized *when they understood something* as exemplified in the statement "Now I understand, last time I did not understand." They could identify *what helps them understand* and *what helps them explain their ideas* as illustrated in the following phrases: "the drawing gives us a tool for explaining," and "it is very clear, I did the experiment and that is what you see in the experiment." They commented on *procedural knowledge that is essential for understanding and for communicating* in this subject matter: "We have to look at the ray diagram," "We have to look at the difference between the rays," and "This is a problem; that is why you have to draw a line from here to there." These exemplary excerpts show that the learners discussed how to use visual explanations; they used ray diagrams in class, but the connection between a ray diagram and a phenomenon is not obvious, and the discourse around the artifacts encouraged them to think about the representation and how it can help them and others.

Another aspect of metacognitive knowledge that is demonstrated in the discourse is *understanding what and how others think*: "…because he thought that he can see the rays," "everyone thought about a different light source," and "he thought that the lampshade changes the light scattering." The discourse demonstrates *diagnostic skills* in the learners' way of thinking. Moreover, there is also evidence of learners *understanding the fundamental parts of the strategy*: "Working in small group is good, because we compare our answers." These examples show that during the discourse, learners talk about their own thinking and about how others think – central elements of metacognitive knowledge.

Evidence for Metacognitive Knowledge in the Learners' Reflection

At the end of each lesson, the learners in group B were asked to answer two reflective questions: What have you learned in the lesson about optics? What have you learned about teaching optics? The purpose of those questions was to promote metacognitive thinking about the lesson regarding both the content and the pedagogy. The following excerpts demonstrate that the learners reported about the development of their metacognitive ability: "This strategy helps me understand others' views and through the discussion I could determine exactly what concepts they know." This learner emphasizes the role of the discussion in understanding what other learners think. The excerpt shows that the learner can reflect on the lesson he had participated in and can recognize its pedagogical aspects. The following excerpts illustrate the understanding of how the strategy helps the learner: "I can learn from my mistakes and from my peers' mistakes"; "Working with peers helps me understand the scientific concepts"; "There are answers that without a discussion with peers you cannot understand them; the discussions help me very much"; "The drawings gave me a tool for explaining phenomena"; "We used the simulation to learn about the phenomena." These examples mention some of the fundamental aspects of the strategy, which were recognized by the learners. The learners also reflect on affective parameters: "The learning was

very interesting"; "The task was challenging"; "It was a pleasant lesson." Another aspect that was found among the learners' reflections is about the teaching and learning strategies that were used: "It is important to work in small groups because you can get new ideas from peers in the group"; "It is important for learners to work individually on a task before they work in small groups."

In sum, the examples we presented illustrate how during the discourse the learners thought about their own way of thinking and how in the reflection after the lesson they demonstrated a metacognitive way of thinking. The learners identified the main components of the learning strategy and realized how the strategy helped them to learn.

Learners' Epistemology

Unfortunately, the CDC strategy did not contribute equally to all learners; for some learners it was very useful whereas for others it was not. The contribution did not depend only on the design of the task or the teacher's scaffolding, but also on the personal parameters of the learners. One of the parameters we identified was the learners' epistemology concerning the goal of learning. In this regard we found two different styles of interaction during the collaborative stage of the CDC. One style of interaction was driven by the desire to find the correct answer, and not to understand why the answer is correct or what led to the correct answer. Another style of interaction was driven by the desire to understand how another group member thinks, or to explain to the group member one's own way of thinking. In these discussions we found a deeper understanding of the physical concepts and how the correct answer is connected to those concepts. The detailed analysis of the results reveals that for the latter group the CDC strategy was far more beneficial than for the first group. These results are congruent with the findings of Abd-El-Khalick and Akerson (2009), who found that metacognitive training and use of metacognitive strategies by prospective elementary teachers influenced their view of the nature of science and ability to explicate more informed views of the nature of science.

Discussion

A common recommendation to teacher educators is that preservice teachers should learn the content by methods that they will be expected to use in their teaching (McDermott 1976). The CDC strategy was developed with this purpose in mind. Thus the strategy is designed to enhance learners' understanding of the content by providing them with opportunities to elicit their conceptions, to discuss them with peers and with their teachers, and to sort out the ideas. We hypothesized that through this process, learners will be able to advance their understanding and develop normative science ideas, and they will also develop their diagnostic capabilities of students' optical ideas.

The results of the study indicate that the preservice teachers developed a high level of conceptual understanding that goes beyond the achievements in traditional courses. They also developed diagnostic capabilities that are neither taught nor tested in traditional courses. At the same time the learners' scores on traditional application questions were not significantly different from those in traditional courses. Thus the CDC strategy indeed has the quality of being a strategy that teachers can use in their classes if they aim to promote their students' conceptual understanding.

Moreover, we suggest that this strategy may provide preservice teachers important learning opportunities not only as learners of the content but also toward becoming prospective learner-centered teachers. The strategy involves a special kind of collaboration with peers in the process of learning: The learners collaboratively diagnose conceptions and their sources, they try to persuade each other in order to reach consensus, and in advanced parts of the course they also discuss ways of supporting students who have mistaken answers in improving their understanding. We propose that through this kind of collaboration the preservice teachers can learn important pedagogical ideas: They have an opportunity to realize that different learners may have different ideas about the same situation and to learn about the alternative conceptions in the particular science topic (e.g., geometrical optics), they can investigate the sources of such ideas and thus become proficient diagnosticians within the particular topic, and they can also think about ways to negotiate meaning and come up with convincing arguments. These are all important elements of pedagogical content knowledge (PCK). These benefits can materialize, however, only if teachers realize the essential characteristics of the instructional strategy and understand their importance. Is this prerequisite guaranteed if we only apply and model the strategy to the teachers as described above? The results of the present study indicate that it is not enough to use the desired teaching strategies – special care should be taken in order to promote the preservice teachers' awareness of the course's teaching strategies as part of their pedagogical content knowledge (PCK). Namely, it is important to scaffold the preservice teachers in developing explicitly their metastrategic knowledge concerning the pedagogy that was used. Metacognition was found to be important for promoting pedagogical content knowledge (PCK). The results reported on pedagogical knowledge of the learners indicate that learners in group A (no reflection on pedagogy) identified significantly less characteristics of the instructional approach than learners in group B (reflection after each lesson). The results show that without scaffolding the reflection on the structure and rationale of the teaching strategy, the teachers did not realize the importance of the collaborative nature of the strategy, and how the strategy can help in communicating about optical phenomena.

The CDC strategy did not contribute equally to all learners: For some learners it was very useful whereas for others it was not. The contribution did not depend only on the design of the task or the teacher's scaffolding; it also depended on the learners' personal epistemology. If one wants to change learner epistemology, one should use the CDC strategy in several courses. A one-semester course is not enough. An interesting future question is whether the preservice teachers will use a similar strategy with their future students.

These results suggest that it is possible to promote PCK in content courses with the help of metacognitive support. Preservice teachers do not do this integration by themselves. The teacher educator in the course should scaffold the pedagogical awareness. We suggest that this should be a compulsory part of the lesson; just providing the opportunity is not enough.

The CDC together with the metacognitive support requires a change in the role of the teacher in the class, toward becoming a guide that supports students' negotiation of meaning among themselves. The teacher in this research was an expert teacher–researcher who knew how to implement the strategy well. The discourse analysis of this teacher's interaction with the groups (not presented in this chapter) showed several effective strategies, mostly metacognitive ones, that this teacher enacted. The knowledge that such a teacher has to possess is extensive, both deep understanding of the particular topics and metastrategic knowledge about effective ways to enable students to learn from each other and advance by themselves through collaboration. Hence, in order to implement this strategy effectively, it is necessary to educate teacher educators as well as leading teachers who will later impart their knowledge to other teachers.

To summarize, our findings indicate the potential benefits that accrue for preservice science teachers that use metacognitive interventions in a content course, for the integrated acquisition of content and pedagogical content knowledge. One of the skills that the CDC strategy can develop is *learning to listen* (Arcavi and Isoda 2007). In the course described in this chapter, the preservice teachers learn to listen to each other. We hope that in this way they will learn how to listen to their future students as well.

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Chapter 11
Toward Convergence of Critical Thinking, Metacognition, and Reflection: Illustrations from Natural and Social Sciences, Teacher Education, and Classroom Practice

Carole L. Ford and Larry D. Yore

Introduction

Open a few issues of research journals on constructivism, conceptual learning, instruction, science and social studies education, and teacher education and you are likely to encounter new hybrids and combinations of well-established stand-alone constructs. Earlier views of learning and pedagogical practices based on behavioralism and cognitive development presented many learner attributes as "fixed traits," learning as a mechanistic process; and many decisions about knowledge construction and actions were made by the teacher rather than the learners. Contemporary perspectives of how people learn promote a much more ecological view of knowledge construction, learner-activated and learner-controlled thinking, and learner characteristics that are amenable to change (National Research Council [NRC], 2000, 2007). This chapter will demonstrate that the intersection of three distinctive traditions in education—philosophy, psychology, and progressive education—has produced common ground and potential power not captured by each lens independently and that this convergence is apparent in many current research studies.

Our separate and collaborative studies and deliberations about these constructs over 15 years support our argument that potential convergence of critical thinking (Ennis 1962), metacognition (Flavell 1976), and reflection (Dewey 1997; Schon 1983) has occurred implicitly in constructivist learning theory and teaching approaches in science and social studies education reforms. This has led to our conclusion that researchers, teacher educators, curriculum developers, and teachers must be explicit about their underlying models of thinking and learning as a

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fundamental platform for education decisions, instructional practices, and research designs. Critical thinking involves self-correction (Lipman 1991), thinking about your thinking to improve your thinking (Paul 1992), or evaluating one's thinking (Siegel 1996) "toward reasonable decisions about what to believe or what to do" (Ennis 1996, p. xvii). Metacognition is considered to be the learner's awareness and management of personal learning and cognitive tasks (Garner 1992) whereas reflection involves "thinking critically about … practice" (Schon 1983, p. 337) and the "knowing which is implicit in action" (p. 50).

Herein lays the problem, or opportunity, as early advocates of these three constructs kept them separate by distinctive focus objects—thinking, cognition, or performance. However, recent scholars have morphed these objects into intersecting domains—constructing understanding; promoting learning, teaching, and even athletic performances. Teaching, once considered a scripted performance that enacted a lesson plan, is now recognized to be a strategic, cognitive, critical, reflective, real-time activity in service of learning: No learning, no teaching. Likewise, learning is believed to be an interactive–constructivist endeavor centered in learners that integrates features of critical thinking, metacognition, and reflection within a sociocultural or sociocognitive context. The remainder of this chapter will attempt to clarify this fuzziness of the borders among these constructs while promoting the potential power of convergence—integration rather than segregation—as the chapter develops.

Reforms in science education (NRC 1996) and social studies education (National Council for the Social Studies 1994) promote contemporary, domain-specific literacy for all students, utilizing constructivist teaching approaches and authentic assessment. Contemporary literacy in both domains involves (a) interacting collections of cognitive and metacognitive abilities, thinking, language, habits of mind, and information communication technologies in construction of understanding of the big ideas and unifying conceptions in science or social studies, and (b) fuller, informed participation in the public debate toward sustainable judgments about science, technology, society, and environment (STSE) issues. Clearly, scientific literacy and cultural literacy is about democratic citizenship and adult life and not about E. D. Hirsh's "litany of facts known by literate people" (McEneaney 2003, p. 230). Correlations (0.78–0.88) among reading literacy, mathematical literacy, and scientific literacy in the Programme for International Student Assessment 2000, 2003, and 2006 stand as potential support for the claim of association amongst language ability, quantitative thinking and science literacy (Anderson et al. 2010).

Our argument is contextualized within contemporary models of learning that recognize the content-specific variations in the nature of discipline (ontology and epistemology), content, and disciplinary discourses, traditions, conventions, and practices. The NRC Committee on Developments in the Science of Learning (2000) stressed three key principles: (a) that people come to learning with prior conceptions about the world (natural and people-built) that must be engaged or challenged if new or refined conceptions are to be developed; (b) enhanced competence requires prior foundational knowledge, conceptual frameworks, and storage, retrieval, and application strategies; and (c) learning requires metacognition to be aware, monitor,

and control meaning making and transference of learning to new situations. People's informal reasoning and intuition provide starting points for developing plausible reasoning, critical thinking, and reflections (NRC 2007). We present brief descriptions of the foundational contexts for critical thinking, metacognition, and reflection (based on philosophy, psychology, and progressive education); summaries of relevant research and experience; and the shared and unique features of critical thinking, metacognition, and reflection. Finally, we provide our insights into promising research, teacher education, curriculum, and instruction using the potential convergence.

Divergent Perspectives

The changing perspective of modern learning theory based on the interdisciplinary cognitive sciences has introduced various interpretations of mind, knowing, and learning that invite reinterpretations of previous concepts related to knowledge, thinking, metacognition, and reflection. The early constructs (critical thinking, metacognition, reflection) grew out of specific historical perspectives (social, economic, and cultural settings) and the scholarship of the times (philosophy, psychology, and progressive education).

Philosophy

The demand for well-grounded judgments to support the ideals of democracy is not new. Socrates questioned grounds for beliefs—both his own and those held by his neighbors. Such rational inquiry into the adequacy of grounds for beliefs underlays the essence of philosophy. Critical thinking, rooted in philosophy, involves rational inquiry to improve the quality of judgments about both beliefs and actions (Bailin et al. 1999; Ennis 1962; Lipman 1991; Paul 1992). More specifically, critical thinking is accountable thinking, a quality of thinking directed to a range of judgments based on relevant criteria and criticality.

Especially relevant to educational philosophy and views of critical thinking is epistemology, a branch of philosophy that involves the critical study of the nature of knowledge (empirical claims)—what it is, why it matters, how it is constructed, and by whom (Tiles and Tiles 1993). Siegel (1992) suggested that "a theoretical understanding of the goodness of reasons, and of related issues concerning truth, fallibilism, rationality and the like … [represents the epistemological position underlying] a coherent conceptualization of critical thinking" (p. 107). Epistemology involves the adequacy of grounds for belief about reality and recognition of the fallibility of human inquiry with implications for notions of certitude while ontology, another branch of philosophy, involves the metaphysics related to reality and the observer—realism, naive realism, idealism.

Psychology

Resnick (1976) stated:

> The measurement of intelligence for purposes of prediction has generally been considered one of psychology's major success stories [in the first half of the 20th century].… Optimism was abundant, both in the possibilities for a social order based on merit and in the power of the psychometrics to provide one of the technological tools needed to bring about such social order. (p. 1)

Unfortunately, there was a lack of a widely accepted theoretical foundation for the underlying constructs and intelligence tests. During the 1950s and 1960s, educational psychologists turned their attention to and focused on behavioralism and cognitive development research devoted to documenting the existence of these approaches' fundamental components in contrived learning environments and with somewhat simplistic learning tasks. Again, dissatisfaction and disappointing results encouraged researchers to search for alternative views of intelligence and learning. The 1970s marked the watershed realization that cognition was neither a simple behavior nor the result of the interactions of concrete experiences and logico–mathematical operations. This led some researchers to interpretations of cognition (sociocognitive, sociocultural, etc.) clustered under the interdisciplinary umbrella of cognitive or learning sciences.

Flavell (1976) proposed that the missing factor in the behavioralist and cognitive development perspectives had to do with considering cognition as the object of consideration and that it consisted of knowledge about the learning and the regulation of learning as knowledge was acquired, developed, or constructed. Flavell stated:

> [W]hat many of us think to be perhaps the central problem in learning and development, [is] namely, how and under what conditions the individual assembles, coordinates, or integrates his already existing knowledge and skills into new functional organizations. (p. 231)

This factor has come to be known as metacognition, and it is considered to consist of two clusters: metacognitive awareness—declarative (what), procedural (how), and conditional (why and when) knowledge—and executive control or self-management—planning, monitoring, and regulating—of the cognition (Garner 1992).

Metacognition in its early forms was controversial, imprecise, and closely connected with beliefs about self, affective dispositions, and motivation. Brown and Campione (1981) suggested that the critical missing component in existing theories of intelligence was the lack of serious consideration of prior knowledge storage, access and retrieval. Much early research in the field of metacognition was focused on the roles of knowledge access in problem solving and reading comprehension, leaving other types of learning and performance for later consideration.

Progressive Education

Industrialization, WWI, and the 1918 influenza pandemic brought rapid, unplanned changes to both urban and rural communities. Urban crowding with its social ills

was exacerbated by immigration and demand for low-cost factory workers that drained labor from rural areas. Traditional roles of the family, community, and church in preparing children for adult life were disrupted, leaving children with limited support for their physical, emotional, spiritual, and intellectual needs (Cremin 1961; Lawr and Gidney 1973). Increased worldwide communications and transportation, new life experiences, increasing international demand and competition for goods, and an insatiable need for workers contributed to a more aware, less compliant citizenry with growing agency and confidence to protest, lobby, and strike to fulfill expectations for a better world. Within this tempestuous socioeconomic context, schooling was viewed by some people as a means to cure societal ills and also a means to social control.

John Dewey, a strong proponent of progressive education and school reform, believed that, rather than forcing the child to fit the curriculum, the curriculum should be adapted to fit the child (Cremin 1961; Gardner 2004). Project-based inquiries should be rooted in children's prior experience; relevant to and motivating for learners; directed to meaningful situations supportive of disciplinary knowledge, conducted collaboratively within a respectful community of learners, and characterized by reflective thinking—disciplined, self-regulated, orderly inquiry directed at well-grounded "beliefs about facts or in truth" (Dewey 1997, p. 3). Dewey was convinced that such a model of scientific inquiry and critical reflection applied across disciplines would be a means to the competencies necessary to well-grounded judgments and the ideals of effective democratic citizenship.

Schon's (1983) analysis of reflective practitioners supported an intuitive practice more responsive to divergent situations and variations in clients' needs. "When intuitive performance leads to surprises, pleasing and promising or unwanted, we may respond by reflecting-in-action…. Reflection tends to focus interactively on the outcomes of action, the action itself, and the intuitive [tacit] knowing implicit in the action" (p. 56). While reflection can be preparatory, reflection-in-action involves spontaneous thinking in real time. However, the time for reflection-in-action can expand according to the "zone of time in which action can still make a difference to the situation … minutes, hours, days, or even weeks or months, depending on the pace of activity and the situational boundaries that are characteristic of the practice" (p. 62). Schon infers that professional practitioners' knowledge-in-action and implicit guiding criteria influence the reflection process.

Research about Critical Thinking, Metacognition, and Reflection

Our struggle to make sense of education in the natural and social sciences led us to examine our segregated ideas about the nature of the disciplines, curriculum, and instruction. We will briefly describe our and others' research in critical thinking, metacognition, and reflection related to learning and teaching the social and natural sciences. The summaries will serve as foundations for a potential convergence model.

Critical Thinking

Ford (1998) developed and explored an integrated, cross-disciplinary perspective of critical thinking and epistemological views of knowledge in social studies. She integrated the extant literature on critical thinking and some aspects of metacognition and reflection into her framework. A mixed methods case study of eight females enrolled in a teacher education program was used to explore the framework. The framework involved an evaluative view of knowledge, cognitive tasks, and the intellectual resources/tools necessary to address cognitive tasks that culminate in sustainable judgments among options about what to believe and what to do. Instruction supported learning about and application of these resources that included the following components:

- *Background knowledge* about a problematic situation/critical challenge, framed as a question or task requiring a judgment among options, serves as the focus and stimulus for the critical thinking; additional intellectual resources learners will need to respond to the challenge, and activities to support attainment of these resources; criteria and standards to judge sufficiency of visions, instructional strategies, and justifications.
- *Criteria and standards for judgment*: Criteria, the parts (e.g., options, reasons, evidence) and qualities (e.g., clarity, accuracy, plausibility, significance, congruence, relevance, sufficiency, comprehensiveness, acceptability, potential effectiveness) contributing to cognitive responses that culminate in sustainable judgments among options about what to believe or what to do; standards, the descriptors identifying the degree that criteria are met.
- *Critical thinking concepts*: Ideas and actions relevant to critical thinking (e.g., point of view, observation, inference, evidence, reason, judgment, criteria, standards, justification).
- *Thinking strategies*: Clusters of complementary methods/ideas to enhance quality of cognitive responses toward sustainable judgments.
- *Habits of mind*: Emotional dispositions or characteristic ways of thinking toward quality cognitive responses when the outcome of judgments matter (e.g., fair-mindedness, open-mindedness, intellectual work ethic, etc.).

Collectively, these dimensions contributed to a definition of critical thinking: *Critical thinking is the self-regulated thinking regarding worthy problematic situations involving evaluative judgments about what to believe or what to do about meaning, relational, empirical, or value claims that clearly illustrate criteria appropriate to quality deliberations, judgment, and justifications.* Self-regulation involved ongoing implicit metacognitive planning, monitoring, and refining responses (oral and written) to critical challenges that strengthen congruence with relevant criteria and intellectual resources. Justifications involved explicit reflection-on-action about the degree of congruence between responses and guiding criteria.

Quantitative data included two pretest–posttest measures: California Critical Thinking Disposition Inventory (CCTDI) (Facione and Facione 1992) and a

semistructured interview protocol (Kuhn 1991). The CCTDI dispositions (truth-seeking, open-mindedness, analyticity, systematicity, critical thinking, self-confidence, inquisitiveness, cognitive maturity) aligned reasonably with the habits of mind in the critical thinking framework. Kuhn's interview protocol utilized the responses to ill-structured problems about social issues (school failure, prisoners' return to crime, unemployment) for evidence of argumentation proficiency and view of knowledge (absolutism—certainty in one correct view of reality; multiplism—many equally acceptable views of reality; evaluativism—open to many views of reality, recognizing some may be more sustainable than others). Qualitative data included instructional artifacts, cognitive tasks, explicit unit and lesson plans and justification for these plans, a written argument about a social situation (school violence), two-way reflective journals, in-class group artifacts, students' formal and informal course evaluations, and an instructor's journal.

An interactive-constructivist approach for instruction was utilized during the 13-week course, which addressed current research trends, learning approaches, and advanced teaching and assessment practices for elementary school social studies. This approach was based on the belief that knowledge is constructed gradually and enhanced by application, depth of inquiry, building connections between existing knowledge and new information, and reflection (collaborative and independent). Key concepts related to social studies, critical thinking, and instructional plans were experienced through immersion, explicit instruction, and application. Critical challenges about significant situations provided reason for deliberating, judging, justifying, and regulating the application of relevant intellectual resources (Ford 1998; Ford et al. 2002; Van Gyn and Ford 2006). Student teachers worked both collaboratively and independently to develop rationales for critical thinking, construct personal visions of ideal citizens, justify sufficiency of visions in light of societal needs and Ministry curricula, generate instructional plans that integrated critical challenges and relevant critical thinking resources, evaluate congruency between visions and instructional resources, and justify their relative potential to move learners toward a sustainable vision.

Study results suggested small gains in CCTDI mean scores and argumentation proficiency (overall moderate strength) and relatively stable views of knowledge with some movement toward evaluativism. This study revealed challenges in clarity of critical thinking concepts and limited congruence among relevant conceptual constructs, with mandated curricula, and between formal and informal measures. Evidence also supported an interactive–constructivist approach to learning that integrates explicit instruction, practice, and reflective application of relevant intellectual resources.

The results also raised epistemological, ontological, and societal concerns. Citizens need an evaluative view of knowledge that embraces multiple perspectives (recognizing some may be better supported than others), acceptance of an external reality that they strive to represent, and a range of intellectual resources when the outcomes of judgments about beliefs and actions really matter. As students gain clarity about the language of critical thinking, they should become better able to

reflect on their thinking and maintain control between their ideas, view of knowledge, and relevant criteria. So too these intellectual resources are essential if curriculum workers, researchers, educators, and their students are to be supported toward sustainable judgments necessary for a critically thoughtful citizenry. Yet relevant literature is mixed in clarity about and commitment to the multiple dimensions of critical thinking/metacognition/reflection and an evaluativist view of knowledge. Requisite to a critically competent citizenry are enablers who value clarity of these constructs, comprehend how they connect to their own ideas, and are committed to strengthening their own intellectual resources.

Metacognition

Cognitive science, constructivism, and educational reforms have repositioned the focus of natural and social sciences education research on learners' prior knowledge, concurrent experiences, and metacognition within a sociocognitive–sociocultural context. Martinez (2006) stressed importance and relationships among metacognitive, critical, and reflective thinking when he anchored metacognition to metamemory, metacomprehension, and problem solving. He suggested that a toolbox of hand tools, measuring devices, and repair supplies was an apt metaphor for metacognition; but he did not fully illustrate the awareness and executive control of these problem-solving materials and the associated cognitive load. Consideration of the capacity in working memory can be illustrated by the novice craftsperson placing all the materials required for the entire repair on the workbench, leaving no room to address the target problem, as contrasted to an expert craftsperson's deliberate and purposeful analysis of the problem and anticipated solution. The expert first selects those specific materials required early in the problem-solving process from the toolbox, leaving working space on the benchtop to place and manipulate the problem object. The expert is metacognitive in planning, monitoring, and regulating actions and command of materials to respect the spatial limitations (M-space). Martin (2004) addressed some of the subtleties and connections to C. L. Ford's critical thinking framework (evaluative judgments about what to believe or what to do) when he pointed out that metacognition "emphasizes the active character of a learner's interactions in learning tasks that results in the construction and reorganization of knowledge structures internal to the learner" (p. 135). Furthermore, metacognition involves "evaluating ideas for their quality, especially judging whether or not they make sense" (Martinez 2006, p. 697).

Metacognition orchestrates the input of information, sensory experiences, and interactions from the sociocultural context; retrieval of prior knowledge and intellectual resources about domain, topic, and cognitive operations or tasks from long-term memory; meaning making in working memory; and integration and storage of new understandings in the existing knowledge stores. Koch (2001) stated:

> Metacognition is a technique that tests reality by checking, monitoring, coordinating, and controlling deliberate attempts to execute learning activity. Metacognition is a hidden level of behavior that involves focusing on conscious knowledge about knowledge and its relation to intellectual performances. (p. 760)

"Metacognition can become so practiced, so normal, that as a mental habit it almost acquires that status of personality trait" (Martinez 2006, p. 698). This is the perplexing part of metacognition from an assessment perspective as it is implicit in most situations where thinking, learning, and reflecting is going well and only becomes deliberate in demanding situations, where difficulties are encountered with the task or where an expert is mentoring a novice to acquire proficiency.

Georghiades (2004) stated, "Metacognitive reflection involves the critical revisiting of the learning process in the sense of noting important points of the procedures followed, acknowledging mistakes made on the way, identifying relationships and tracing connections between initial understanding and learning outcomes." (p. 371). He elaborated that "metacognitive monitoring … entails more than passive observing. It requires an element of judgment.… This judgment-laden reflective feedback will later enable the metacognitive learner to take informed action for rectifying the situation" (pp. 371–372). This interpretation parallels aspects of critical thinking in C. L. Ford's framework.

Recent models of reading informational text has involved "making sense of text", not simply "taking meaning from text", which requires a critical, reflective, self-regulated reader. Three research studies that used the contemporary description of metacognition as consisting of two clusters are provided below. The Index of Science Reading Awareness (ISRA) (Yore et al. 1998) was designed to measure metacognitive awareness of science reading. The ISRA consists of 63 items on a 21 × 3 framework of the successful and efficient science reader: *A flexible, strategic person who is aware of and manages her or his science reading, use of science text, and uses science reading strategies to construct understanding within a specific sociocultural context*. The 21 vertical dimensions of the framework were based on an interactive–constructive model of reading and a synthesis of reading research that was applied and related to science reading, science text, and science reading strategies; the three horizontal components were related to the components of metacognitive awareness of each strategic dimension. The original ISRA recognized the difficulties in documenting metacognition and that knowledge about cognition does not ensure its use to manage and control.

Study 1

Spence et al. (1999) explored reading comprehension and metacognitive changes of an intact Grade 7 class (14 males, 13 females) using a pretest–posttest case study over a 22-week program of study. The instruction focused on the nature of science, technological inventions, properties of matter, and classification and composition of living things with embedded explicit reading comprehension instruction (features and organization of information text, accessing prior knowledge, using contextual clues to define terms, identifying main ideas, and summarizing). Reading comprehension and metacognition were assessed using (a) a direct measure of understanding following reading of a science passage not involved in instruction and (b) a modified

ISRA extended into a subtest of the self-management of four target strategies: accessing prior knowledge, identifying and using text structure, finding main ideas, and writing summaries.

Results revealed positive relationships between metacognition and success on reading comprehension tasks. Analysis of gain scores indicated significant enhancements in students' metacognition and their ability to comprehend science text across all reading abilities. A significant gender difference favoring females was found for self-management. Qualitative evidence indicated that the most likely candidates for successful metacognition instruction were students in the upper-lower to upper-middle achievement groups.

Study 2

Holden and Yore (1996) explored Grade 6/7 students' attributes in learning about the endocrine system, nervous system, and lifecycle of plants in five classrooms. The teachers used a common 11-week course of study and instructional approach focused on explicit reading comprehension instruction (accessing prior knowledge; setting purpose; monitoring progress; compare–contrast, cause–effect, and description genres; and detecting main ideas) embedded in a modified learning cycle. This pretest–posttest case study ($N = 87$) documented the metacognition changes (modified ISRA), content knowledge growth, and student attributes. Prior conceptual knowledge and science achievement were measured by a 19-item objective test developed to reflect the content focus from a pool of validated items associated with the program of instruction (internal consistency = 0.53). Student attributes considered learning styles measured by the Group Embedded Figures Test (GEFT) (Oltman et al. 1971) and the Learning Preference Inventory (LPI) (Silver and Hanson 1978). The GEFT was used to determine cognitive style along the continuum of field-dependence to field-independence, while the LPI was used to determine the students' personality-based, perception-judgment styles (sensing/feeling, sensing/thinking, intuiting/thinking, intuiting/feeling).

Results of the learning styles and learning preferences indicated that most (56%) students had no distinctive field-dependent or field-independent style and most (73%) students preferred the feeling orientations. We found small but significant correlations between the GEFT, prior knowledge, and pretest metacognition. Significant differences were found between groups of students with identified cognitive style for gains in science achievement, metacognition, and metacognitive awareness but not for self-management. Similar significant differences were found for levels (high > low) of pretest metacognition, metacognitive awareness, and self-management and science achievement gains (posttest–pretest scores). This appeared to indicate the general importance of entry-level science reading metacognition on learning in science programs that use print materials to supplement hands-on experiences.

Study 3

This mixed methods case study (Yore and Holden 2005) explored the consistency of measures across different metacognition assessment methods and the relationship of the students' metacognitive awareness with their strategic performance. Pre- and post-ISRA and pre- and postinterview protocols with embedded performance tasks designed to elaborate the information about reading strategies were used to document metacognitive awareness and self-management of six science reading strategies (utilizing self-confidence to address comprehension difficulties and failures, text structure/genre, setting purpose, detecting main ideas, self-questioning to monitor comprehension, and utilizing mental images to support comprehension). The 71 Grade 6/7 volunteers were randomly assigned to six clusters of 11–12 students who were tested and interviewed to document their metacognitive awareness, self-management, and science reading performance of a target strategy identified earlier. All students received the same program of instruction between the pre- and post-assessments.

The metacognition interview questions were oral versions of the related ISRA items. Reading performance was documented by providing text not covered in the program of instruction that involved a target strategy and asking students to provide a think-aloud while they made sense of the text and explained a target strategy. The interviews were recorded, and responses to the interview questions and reading performance tasks were scored by four evaluators (interrater agreement was 81.3–85.5%) using the same criteria for the open response option of the ISRA (Yore et al. 1998). The interview responses were further analyzed using constant comparison to identify trends in the responses and performance task. The analysts proposed potential assertions and identified supporting evidence for each protocol independently. Follow-up discussions and repeated analyses confirmed or modified assertions to reach consensus.

Correlations of posttest results and reading performance and postinterview and reading performance were conducted to determine the degree that students demonstrated associations between their metacognition and their use of that metacognition in science reading performance. Small positive and negative correlation coefficients suggested discrepancies between metacognitive knowledge about a reading strategy and actual performance for that strategy—*Knowing does not ensure use* (Garner 1992). Qualitative analyses of the interview responses revealed that:

- These students' metacognitive knowledge about science reading was a text-driven interpretation of reading as taking meaning from text—*Not* the interactive–constructive interpretation of reading as making meaning from text, and their limited control of comprehension difficulties required external expert help.
- These students' metacognitive knowledge about science text was very limited; they lacked general awareness and control of compare–contrast text structure (genre) to plan and support reading performance and had little insight into how to proceed or control note taking based on the genre.

- These students started out with surface awareness and limited control of detecting the main ideas but improved to much stronger awareness and reasonable control of this strategy, and their application of this strategy was very good.
- These students demonstrated very little or irrelevant knowledge about and control of self-questioning as a monitoring strategy, but they demonstrated improvement over the duration of the study.
- These students demonstrated surface knowledge about and control of using mental images, but they demonstrated better application of the KWL (prior Knowledge, What are the target outcomes, and ideas Learned) strategy in their reading performance than in the interview.

The major findings of these three studies revealed how little explicit instruction these students had with informational text, how poorly they scored on the ISRA and interview protocols, how poorly they performed and explained specific science reading tasks, how difficult it is to improve science reading metacognition and performance, and how influential metacognition is on science learning in an inquiry context with embedded textual materials. The studies' results support White's (2003) assertions that metacognition is "learnable … [and] that possession and use … determine students' abilities to learn" (p. 1207) a variety of subjects. He provided suggestions into improved metacognition research that imply the need to consider the nature of the target discipline, critical thinking and reflection, establish relations between enhanced metacognition and conceptual learning, and develop valid and reliable assessment tools. However, the continual problem is to find situations and tasks that place cognitive demands on people while maintaining positive motivation to make their metacognition deliberate and public.

Reflection

Much of our experience with reflection has involved clinical supervision of preservice teachers considering their teaching post hoc and the action research projects of graduate students studying the implementation of a pedagogical innovation. In both cases, we played the role of a more experienced peer or a critical friend who served as the intellectual mirror for their reflective thinking about their performance, action, or thinking. The external reference involves sharing questions, seeking justifications for actions or decisions, and inserting or explicating criteria, standards, or goals. Our combined experiences have illustrated the value of reflection in constructing understanding and improving practice. The goal in using reflection-on-actions is to help the person to move these considerations, deliberations, and controls to real-time reflection-in-action.

Distinctions between reflection, critical thinking, and metacognition/self-regulation are often unclear; and the concepts have been used interchangeably (McAlpine et al. 1999) or as a subset of the other (Lapan et al. 2002). Common across notions of reflection is deliberate, focused thinking—qualities also characteristic of critical thinking

and metacognition. Reflection may be critical but it need not be, as when one simply recalls events. Critical reflection moves to deciding what to believe and what to do and may aspire to learning or social change (Mezirow 1991; Procee 2006).

Our considerations of reflection have included the focus objects, time, conditions, and elaborations to aid clarity for instruction, assessment, curricula, and research. Recent research identifies objects of reflection in performances (teaching, thinking, learning) and products (beliefs, understandings or representations of ideas). Kreber (2005) identified three kinds of reflection (content of a problem, process or problem-solving method, and premises underlying the problem) within three domains of instructional knowledge (instructional planning/design, learning and instruction, and curricular goals and their congruence with societal goals). The resulting 3×3 matrix represents nine forms of knowledge as objects of reflection. Kreber used a semistructured interview with 36 science instructors to document the model. Across all three knowledge domains, there was limited evidence for reflection about premises (most often, teaching strategies were changed to better realize goals rather than subjecting goals to critical reflection), most frequent evidence for reflection about process, and limited concrete evidence of declarations of reflection. McAlpine et al. (1999) identified three spheres of knowledge (practical knowledge about how to improve action, strategic knowledge about teaching across contexts, and epistemic or cognitive awareness of one's own reflection and how it can impact reflection and performance) as objects of reflection.

Time for reflection may be before action, during action, and after action (Lapan et al. 2002; Saito and Miwa 2007). Reflection-in-action can range from seconds to months, the time during which action can still make a difference (Schon 1983). Evidence of reflection before or after action has been gathered in journals, interviews, and audiotapes or videotapes; evidence of reflection-in-action has been more challenging to document. It appears that the use of "think alouds" during real-time and video-tape replays of practice may aid documentation of reflections-in-action.

Conditions to facilitate reflection for learners vary, ranging from student–student and student–teacher interactions and expectations for reflection (Peltier et al. 2006) to kinds of instructional support for reflection; for example, software support that provides prompts/questions, displays of learning processes, models for comparison, experts' annotations connected to the target products, collaborative support from a critical friend, and differences in preferred support (Saito and Miwa 2007; Song et al. 2006). Peltier et al. (2006) found more evidence of higher levels of reflection among undergraduate marketing students in interactive rather than lecture-based contexts and stronger student perceptions of quality learning associated with a program involving intensive, deep reflection. Saito and Miwa (2007) found that multiple forms of support for information seeking on the Web were effective in changing ideas and search procedures, compared with the control group. They posited that students able to perform relevant reflections spontaneously would be successful in meeting relevant library standards (e.g., effective, efficient location of needed information; use most appropriate methods; effective search design; variety of methods, refined when needed; and systematic recording and management of information and sources). Song et al. (2006) found that groups of students differed

significantly in preferences for kinds of support for reflection. The middle-school group faced with an ill-structured problem about aeronautics and remote sensing favored a constructivist learning environment, whereas the college-level students faced with a similar ill-structured problem requiring application of introductory statistics preferred teacher-facilitated methods.

The collective research on reflection points toward inconsistent interpretations, efforts toward clarity, diversity in objects of reflection that emphasize practice, limited evidence of reflection on premises underlying practice, promising evidence for documenting reflection-on-action, and evidence that multiple forms of support enhance the quality of reflection-on-action and reflection-in-action. Explicit use of language of reflection, interactions among students and between students and instructor, high expectations for intense reflection, and use of multiple forms of support are congruent with stronger reflections and improved performance.

Overlapping constructs and objects of thinking reveal fuzziness and/or exploration of relationships among critical thinking, metacognition, and reflection. Illustrations of how the three constructs have been distinguished and existing/potential areas of convergence may enhance clarity about them, facilitate testing congruence with our own ideas, and illuminate possibilities for increasing the power of our ideas toward quality thinking.

Critical Thinking, Metacognition, and Reflection: Toward Convergence

Evolving models and theories of learning over the last 60 years (behavioralism, cognitive development, constructivism) have resulted in changing needs to redefine and integrate these three powerful constructs. The reform documents in science education and social studies education in many countries call for disciplinary literacy for all students, constructivist-oriented teaching, and authentic assessment; and a taskforce report on how people learn (NRC 2000) stressed the importance of quality thinking, metacognition, and reflection. Inspection and critical deliberations of our interpretations of critical thinking, metacognition, and reflection and the collective literature revealed common dimensions and concerns: complexity of associated concepts; evolving definitions; the need for explicit teaching, application, and reflection about associated concepts; deliberate and explicit considerations of criteria or standards; views of knowledge; knowledge does not ensure use, and problems of assessment and documentation. The definitions of these constructs deal with *thinking about your thinking/learning/actions to improve your thinking/learning/actions as you are thinking/learning/acting, which in turn will enhance the thinking/learning/actions*. The quality of critical thinking, metacognition, and reflection of teachers may well be fruitful starting points for effective instruction and high-quality learning. J. Bruner's (Ramsden 1992) comment is germane: "I would be content if we began, all of us, by recognizing that discovering how to make something comprehensible to (our students) is only a continuation of making something comprehensible to

ourselves in the first place." (p. 150). Once we enhance personal clarity, we need to help learners do the same—teaching in service of learning; without learning, there is no teaching.

Internalization and personal understanding involve constructing consistent conceptual frameworks that allow the knower to address novel and complex issues and problems. This requires detecting important procedural moves and mistakes, identifying connections and relationships between new ideas and prior knowledge, and testing the accuracy/plausibility and fit between new and prior knowledge. Furthermore, meaningful understanding is the starting point for developing a compelling case for the value of this knowledge, constructing powerful structures, and sharing/inspiring/supporting others to do the same. Within the interactive–constructive model of learning science and social studies we have presented, sharing and facilitating involve more than telling others. Yet research suggests that educators who may be adept at integrating critical thinking, metacognition, and reflection into their own thinking may not be as proficient in clarifying relevant expectations, criteria, and standards for others. Being knowledgeable about these constructs does not ensure utilization of the knowledge in real-time applications. Citing the components and conditions of critical thinking does not ensure that you are an effective critical thinker; knowing about metacognition does not ensure that you control your thinking/learning; and reflecting-on-actions does not ensure that you can reflect-in-action.

Limited, clear, comprehensive, operational definitions of these separate constructs within contemporary views of learning have led to difficulty in assessing and documenting critical thinking, metacognition, and reflection. Our successes and difficulties in assessing these constructs have encouraged us to consider a composite instrument that would couple specific components into a unified measure—view of knowledge, dispositions, kinds of judgments, relevant tasks, background knowledge, criteria and standards, and other resources needed for sustainable judgments, constructing understanding, or improving performance. This central concern stimulated a search for an integrated framework that would identify similarities (shared features) and differences (unique features) for these three stand-alone constructs.

Relationships between or among critical thinking, metacognition, and reflection—as they relate to kinds of judgments and intellectual resources—provide useful insights for curriculum workers, researchers, and educators. Furthermore, they connect formerly isolated literatures and discourses about knowledge construction, plausible reasoning, argumentation, and self-regulated learning. Figure 11.1 represents the union and intersection of critical thinking, metacognition, and reflection in a Venn diagram. The intersections describe potential convergences where two or three adjacent constructs overlap. The center of the diagram articulates the shared features among the three constructs; it illuminates the potential power in convergence of critical, metacognitive, and reflective thinking when integrated with the intellectual resources that enable sustainable judgments for beliefs and actions. The intersections of two constructs illustrate the shared features between construct pairs, while the outlying areas in the union of these constructs contain features that have distinguished the individual constructs.

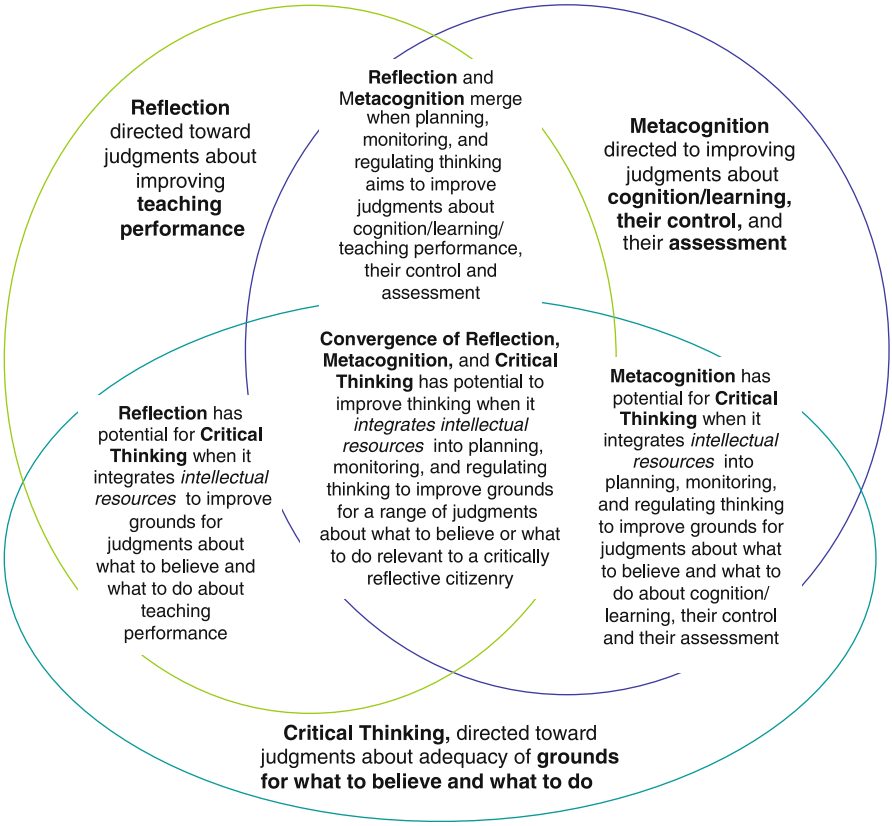

Fig. 11.1 Toward convergence of critical thinking, metacognition, and reflection

Early representations of these isolated constructs considered very limited applications and were frequently composed of sequenced lists of skills. Critical thinking, in its pure sense, focused on grounds for belief, that is, thinking directed toward judgments to improve congruence between grounds and beliefs. Metacognition focused on knowledge of cognition/learning, that is, thinking directed toward judgments to improve our knowledge and control of cognition/learning. Reflection in education focused on practice and knowledge embedded in practice toward judgments to improve practitioner performance. The integrated view of these constructs expands the applications to include a variety of learning, reasoning, and performance domains and illustrates that knowledge about, control of, and reflection on these various ideas, intellectual resources, events, beliefs, or actions are central to high-quality and sustainable outcomes about what to believe and what to do.

Convergence becomes apparent when the range of focus outcomes is expanded to include a variety of claims and actions. The isolated nature of these individual constructs arises from their origins and initial foci: grounds for belief, cognition/ learning, or teaching performance. Reflection and metacognition merge when they

are directed toward judgment to improve the quality of knowledge about and control of cognition/learning/teaching performance: what it looks like, how it can be assessed, and how knowledge of cognition/learning/teaching performance can be utilized to enhance cognition/learning/performance-in-action. Reflection has potential for critical thinking when integration of relevant intellectual resources into judgments about what to believe or what to do toward well-grounded performances is conscious, enabling explicit justifications about grounds for judgment (e.g., *effective* teaching options will maximize learners' potential to demonstrate desired objectives/goals). Metacognition has potential for critical thinking when metacognitive tasks (planning, monitoring, and regulating knowledge of cognition/learning) and their control and assessment are integrated with relevant intellectual resources, thereby enhancing prospects for sustainable judgments and explicit justifications about which claims or actions align best with relevant sufficient criteria/grounds.

Real-world challenges—like most STSE or socioscientific issues—can be messy, complex, and interdisciplinary; they may require a range of judgments about tradeoffs, sustainability, maximization, etc. We believe that these challenges central to social studies and science literacies can best be addressed using a convergence lens and that it has been less productive to address these judgments through the isolated lenses of the independent constructs. Responsible, informed educators need to generate worthy, authentic challenges that their students care about, that connect in meaningful ways to the cultural and academic knowledge, beliefs and experiences students bring to class, and that require over time a range of judgments about planning, monitoring, regulating, verifying, and evaluating cognition/learning/teaching/actions toward sustainable outcomes. These challenges provide motivation and context for explicit "just-in-time" teaching about and student application of intellectual resources to different kinds of judgments.

Concluding Remarks

We believe critical thinking, metacognition, and reflection are essential components of fundamental literacy related to the natural and social sciences that when engaged sufficiently, fulsomely, and comprehensively produce greater understanding of the big ideas in the natural and social sciences (Yore et al. 2007). The convergence of these constructs does not include all aspects of each construct but focuses on views of knowledge (ontological assumptions and epistemological beliefs); rational inquiry; thinking outcomes; reflection on a variety of cognitive, psychomotor, and affective performances; awareness of the performance; and executive control of the performance. These aspects include but are not limited to:

- Considering worthwhile challenges, issues, or problems.
- Building knowledge claims and making sense of the natural and constructed world.
- Analytical reasoning, critical thinking, problem solving, and troubleshooting.

- Creative thinking that involves generating possibilities and alternatives.
- Planning, evaluating, and justifying inquiries, designs, explorations, investigations, actions, performances, etc.
- Deliberating evidence, criteria, standards, opinions, and arguments leading to claims.
- Observing, measuring, inferring, predicting, representing, and investigating.
- Judging and explicating the sufficiency and congruency of criteria, alternative beliefs, and actions and then refining them as needed.
- Critical analysis of claims, procedures, measurement errors, evidence/reasons, data, information sources, etc.
- Justifying data as evidence for/against a claim based on sufficiency of the theoretical backings/warrants and the congruency of evidence, judgments, and claims.
- Thinking about and logging specific intellectual resources used in deliberations, judgments, and justifications; evaluating their personal effectiveness toward the goal; and identifying other situations for which they might be helpful.

Several research agendas have applied converged perspectives of critical thinking, metacognition, and reflection to a wider range of ages, domains, and topics. A few of these endeavors involve metacognitive development in young children (Larkin 2006), postsecondary students (Case and Gunstone 2006), and science teachers (Leou et al. 2006); affective character of metacognitive experiences (Efklides 2006); interpreting popular media reports (Norris et al. 2009); quality and effects of written arguments (Hand 2007); promoting inquiry (White and Frederiksen 2005); describing principles of effective college teaching (Bain 2004); and self-regulated learning (Hadwin 2008; Schraw et al. 2006; Winne and Hadwin 2010). These efforts toward convergence illustrate implications for curriculum workers, teachers, teacher educators, and researchers. Thomas (2006) asked, "What other important life-long attributes, apart from learning and understanding science, might and should be developed in students within their science learning environments?" (p. 1). He suggested that higher-order thinking, metacognition, and reflection would be among the outcomes of any metacurriculum focused on disciplinary literacy, citizenship, and adulthood.

We would say that critical thinking, metacognition, and reflection could realize even more promise if the convergence framework is applied. This perspective opens natural and social sciences education research to a broader array of literature and discourse that addresses the fundamental nature of the disciplines and their material and social practices in knowledge construction (Ford 1998, 2008). Evidence from research that supports integration of two or three of these constructs provides insights and promise for future research, curriculum work, teacher education, teachers and learners; it also parallels contemporary principles of learning. Benefits for science and social studies education are found in the awareness and self-regulation of thinking that integrates intellectual resources for critical thinking, an evaluative view of knowledge, and recognition that major conceptual changes—including ontological and epistemological positions—can be difficult and that accommodation does not progress smoothly. Dewey's (1998) notion of a reflective, independent

citizenry that is rigorous about worthwhile issues and sufficiently prepared to make well-grounded judgments is central to demonstrating intellectual and moral possibilities for a better world.

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