Metacognition Learning (2008) 3:59–82
DOI 10.1007/s11409-007-9019-4

Explicit teaching of meta-strategic knowledge in authentic classroom situations

Anat Zohar · Adi Ben David

Received: 5 August 2006 / Accepted: 14 December 2007 /
Published online: 30 January 2008

Abstract Meta-strategic Knowledge (MSK) is a sub-component of metacognition that is defined in the present study as general, explicit knowledge about thinking strategies. In the present study we shall focus on the control of variables thinking strategy. Following an earlier study (Zohar & Peled 2007) that showed considerable effects of explicit instruction of MSK in laboratory setting, this study explores whether these effects are preserved in authentic classroom situations. Participants were 119 8th grade students from 6 classes of a heterogeneous school. Equal numbers of low-achieving and high-achieving students were randomly assigned into experimental and control groups. The findings showed dramatic developments in students' strategic and meta-strategic thinking following instruction. The effect of the treatment was preserved in delayed transfer tests. Our findings show that explicit teaching of MSK had a strong effect on low achieving students. The implications of the findings for learning and instruction are discussed.

Keywords Metacognition · Meta-strategic knowledge · Meta-cognitive knowledge · Low achieving students · Higher order thinking skills and strategies · Control of variables thinking strategy

Introduction

Meta-strategic Knowledge (MSK) is a sub-component of metacognition that is defined in the present study as general, explicit knowledge about the cognitive procedures that are being manipulated. The cognitive procedures we are referring to are comprised of higher order thinking strategies. Examples of such thinking strategies may include: solving problems, classifying, establishing and analyzing causal relationships, constructing good arguments, formulating research questions, testing hypotheses, drawing valid conclusions

A. Zohar (✉) · A. B. David
School of Education, Hebrew University, Jerusalem 91905, Israel
e-mail: msazohar@mscc.huji.ac.il

A. B. David
e-mail: bendaa01@mscc.huji.ac.il

or controlling variables. Accordingly, most of the traditional inquiry thinking strategies are included in these cognitive procedures. The pertinent metacognitive knowledge is an awareness of the type of thinking strategies being used in specific instances. Although most of the components of this knowledge may be either implicit or explicit, its application in classroom use is always explicit, and its components can be publicly discussed and negotiated in class. It consists of the following cognitive procedures: making generalizations and drawing rules regarding a thinking strategy, naming the thinking strategy, 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. In the present study we shall focus on MSK in the context of control of variables.

Our 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 to students' reasoning. There may be a variety of pedagogical ways for teaching MSK, such as reflecting on others' performance on a task, or engaging a series of written meta-level exercises (see Kuhn et al. 2004; Pearsall 1999). Nevertheless, the pedagogical way embraced in the present study 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 meta-strategies. 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 2 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 then addressing it only in an abstract way.

A previous study (Zohar and Peled 2007) investigated the effects of explicit teaching of meta-strategic knowledge (MSK) on reasoning ability of low-achieving and high-achieving students. That study was conducted with a small number of participants in controlled laboratory conditions. The goal of the present study is to elaborate the previous findings by examining the same phenomenon with a larger number of participants in authentic school conditions.

Theoretical background

The modern era which is characterized by enormous quantities of scientific and technological information that changes rapidly and continuously, requires changes in the goals and methods of education. Learning and instruction is moving from an emphasis on acquisition of basic skills and large amounts of information to an emphasis on deep understanding and the development of reasoning skills that will enable students to acquire and process new knowledge. Furthermore, recent education curricula emphasize the need 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). 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. 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.

Raudenbush et al. (1993) revealed that teachers 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, believe that it is appropriate only for HA students. These teachers believe that higher order thinking is inappropriate for LA students who should be taught by a transmission of knowledge approach. This belief may become a self-fulfilling prophecy, because teachers would tend to avoid the use of higher order thinking activities with LA students who would be "stuck" at learning that emphasizes memorization and methods of drill and practice. A more recent study (Warburton and Torff 2005) similarly demonstrated that teachers rated both high and low critical thinking activities as more effective for high-advantaged learners than for low-advantaged learners. Since at least one of the reasons for such beliefs is teachers' feeling that they lack satisfactory instructional means for teaching thinking to students with low academic achievements (Zohar et al. 2001), it is imperative to develop such instructional means and assess their effects for LA students. Our research examines one such potential educational means: explicit teaching focusing on a sub-component of metacognition which we term meta-strategic knowledge (MSK).

Anchoring the concept "MSK" in previous research

As has recently been confirmed by Veenman et al. (2006) the domain of metacognition is one that lacks coherence. Consequently, the relation of some specific terms relating to metacognition with the overall concept of metacognition is often not clearly defined. Therefore, rather than simply define the relationships between MSK and metacognition, we need to analyze the literature in order to examine how MSK relates to various metacognitive components according to prominent previous researchers. For instance, Flavell et al. (2002) divided metacognition into metacognitive knowledge and metacognitive monitoring and self-regulation. He then further divided metacognitive knowledge into three sub-categories: knowledge about persons, tasks and strategies. The latter two sub-categories are related to MSK because the task sub-category concerns the nature of the task demands and the strategy sub-category concerns the nature of the strategies that are likely to succeed in achieving specific cognitive goals. Schraw (1998) made the distinction between regulation of cognition and knowledge of cognition that is again further divided into declarative, procedural and conditional knowledge. MSK is related to the two latter sub-categories. 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). Conditional knowledge refers, among other things to knowing when and why to use strategies.

The definition applied in the present study however, is closest to the definition formulated by Kuhn who studied MSK in an extensive way (Kuhn 1999, 2000, 2001a, b; Kuhn et al. 2004). The concept of MSK that is used in the present study is tightly linked to

Kuhn's procedural meta-level knowing, which addresses two main questions: (a) what do knowing strategies accomplish? And, (b), when why and how to use them? Kuhn proposes that meta-strategic understanding consists of two components: one is the understanding and awareness of the nature and requirements of the task. The second is awareness and understanding of the strategies of one's repertory that are potentially applicable to the task. Kuhn views the challenge of effective meta-strategic thinking as one of coordinating the two components, namely understanding of the task and understanding of potential strategies (Kuhn and Pearsall 1998). For a more detailed conceptual analysis of MSK please see Zohar (submitted for publication).

Explicit teaching of meta-knowledge about the control of variables strategy in previous studies

Previous studies investigated the effects of knowledge that has much in common with the knowledge discussed in the present study while using a different conceptual framework. Researchers in these studies investigated the effects of explicit teaching regarding the principles of the control of variables strategy without addressing the concept of MSK. Ross (1988) performed a meta-analysis of 65 studies that examined methods for teaching students how to use the control of variables strategy. Although he did not mention the concept MSK, Ross demonstrated the benefits of explicit instruction that focuses on understanding of procedures and design features which clearly has a considerable overlap with the issues addressed by the concept of MSK. Ross concluded that treatments that made the constituents elements of the control of variables schema explicit to students through a set of overt procedures or salient examples had a greater impact than treatments in which the operations that make up successful performance were less visible. The same finding has been repeated by Chen and Klahr (1999) and by Toth et al. (2000), who showed that 7- to 10-year-olds were able to learn and transfer the control of variables strategy when provided with explicit training. Teaching with no explicit training did not improve children's reasoning abilities in a similar way. In a more recent article Klahr and Nigam (2004) again measured the relative effectiveness of discovery learning versus direct instruction in which the control of variable strategy was explicitly taught. The findings showed that many more children learned from direct instruction than from discovery learning. Moreover, when asked to make broad, rich scientific judgments one day after instruction, children in the direct instruction group performed as well as those few children who discovered the method on their own.

However, Dean and Kuhn (2007) criticize the work by Klahr and Nigam (2004) on the grounds that it did not examine maintenance over a longer time period. Dean and Kuhn thus followed students' mastery of the control of variables strategy over a longer time period—almost 6 months—across varied content. Their hypothesis that under such more extended assessment the relative strengths of direct instruction and discovery might appear in a somewhat different way was confirmed. Their findings show that in this longer-term framework direct instruction appears to be neither a necessary nor sufficient condition for robust acquisition or for maintenance over time. These apparently contradictory findings call for an additional examination of the learning conditions under which explicit instruction is carried out, of the student population it addresses, and of its outcomes.

One of the goals of the present study is to examine how explicit metacognitive instruction affects various parts of the student population, or more specifically, how it affects HA and LA students. White and Frederiksen (1998, 2000) found that the effect of addressing metacognitive knowledge explicitly during instruction is even more important for students with low academic achievements than for students with high academic achievements. The explanation for this finding is that students with high academic achievements often manage to construct elements of metacognitive knowledge by themselves. Students with low academic achievements however, are less able to do so. Treatment that focuses on metacognitive knowledge therefore makes a greater difference for their thinking. Since this study addressed various components of metacognition rather than specifically MSK, it leaves open the question of whether explicit instruction that would focus specifically on MSK would have similar benefits for LA students.

To further explore this issue, the general goal of a previous study conducted in our research group was to study the conditions under which explicit instruction of MSK would be effective, and to examine how it would affect the thinking of low-achieving and high-achieving students (Zohar and Peled 2007). That study assessed the effects of explicit teaching of MSK on gains of low-achieving (LA) and high-achieving (HA) 5th grade students (n=41). Gains in reasoning scores of students from the experimental group (compared to students from the control group) were obtained on the strategic level and on the meta-strategic level. 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 who required a longer period than HA students to reach their top score.

However, that study was conducted in laboratory conditions, in the sense that participants comprised of a small group of students who participated in a long-term, one-to one interaction with the experimenter. In order to be able to generalize from such "sterilized" conditions to the "messy" conditions that exist in real classrooms, where one teacher is often responsible for the learning of 30 children, a new study is required. The goal of the present study is therefore to extend the scope of our previous study in order to find out whether its findings would be repeated in an authentic school setting.

Research questions and hypotheses

1. What are the effects of explicit teaching of MSK in an authentic school setting on the development of students' strategic and meta-strategic thinking regarding the control of variables strategy?
2. How does such explicit teaching of MSK affect transfer and delayed transfer (retention)?
3. What are the differences between LA and HA students concerning questions 1 and 2?

Based on the findings described in the literature review, our hypotheses are: (a) that explicit teaching of MSK in an authentic school setting will have a positive effect on students' strategic and meta-strategic thinking; (b) that this effect will be preserved in transfer and delayed transfer tasks; and, (c) that LA students will benefit from the treatment more than HA students.

Methodology

Participants Participants were 119 school students aged 13–14 years (45 boys and 64 girls) who study in six grade 8 classes of the same public school in a large city. The student population is mixed, ranging from middle-high to low social-economic status (SES). The school's policy is to create classes of children with mixed ability in the sense that, based on children’s background data and achievements in elementary school, the school tries to assign more or less equal numbers of low-achieving, medium-achieving and high-achieving students to each class, as well as balancing the classes in terms of children's backgrounds and learning and behavioral problems.

Research design The six classes were randomly divided into the 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. Students whose mean score was above the median (78) were classified as HA and students whose mean score was below the median were classified as LA. It is important to note that the year end 7th grade report card consisted of 11 different grades (given by different teachers) of 11 subjects: literature, history, grammar, bible, algebra, geometry, two foreign languages (English and Arabic) geography, art, science and technology. Therefore we viewed the mean scores of the report cards as a highly reliable source for determining students’ academic level and we had a high level of confidence in using it to classify students as either HA or LA. The classification into the HA and LA groups was taken into account only in the stage of data analysis, so that students of both levels received the same treatment. At the stage of data analysis we thus had a total of four experimental sub-groups in a 2X2 design: LA experimental sub-group (N=30), LA control sub-group (N=29), HA experimental sub-group (N=30), and HA control sub-group (N=30).

The study was designed as part of a curriculum in which we taught the biological topic of reproduction by using a set of 10 consecutive short inquiry learning activities taken from the Thinking in Science Classrooms (TSC) project (Zohar 2004) and adapted for the purposes of the present study. The curriculum was taught over a period of 12 science lessons.

All students engaged for the same amount of time in various inquiry tasks that required, among other things, control of variables, i.e., to compare between at least two cases while keeping all variables constant except the target variable. Only students in the experimental sub-groups received explicit instruction about MSK in the context of control of variables. The content of the explicit MSK instruction consisted of the following elements (Zohar, submitted for publication):

- Knowing the name of the strategy (i.e., control of variables).
- Recognizing the necessity to control variables if the resulting inferences are to be valid and recognizing *why* inferences that are made without controlling variables are invalid. This knowledge consists of an understanding that if in a certain comparison we are changing more than one variable in each comparison, we cannot say for sure which variable makes a difference (in cases in which the outcome varies across various instances of the comparison). Alternatively, in cases in which the outcome remains the same across various instances of the comparison, we cannot know for sure that no variables made a difference because various variables could have compensated for each other. This knowledge component addresses the “why” component of the definition.
- Knowing how to use the rule, i.e., compare between at least two cases in which all variables remain constant except the target variable. Also, knowing how not to use the rule, i.e., knowing that it is wrong to change more than one variable at a time. This knowledge component addresses the *“how*” component of the definition.
- Being able to identify when to use the control of variables strategy. i.e., knowing that variables need to be controlled whenever we need to establish the existence of causal relationships. This knowledge component addresses the *“when*” component

of the definition. It can also be viewed as understanding what type of tasks call for the use of the strategy and thus it can be viewed as addressing the "task characteristic" component of the definition.

The study was conducted during 12 consecutive science lessons in which students learned selected topics in Reproduction. Data collection was conducted by assembling written activity-sheets that students were required to complete as part of their learning process (see below).

The research design is summarized in Table 1 and described in more detail in the following sections.

Ethical considerations

Since Ethics was one of our main concerns in this "natural classroom" study, we made sure that children from both the experimental and control group received the same amount of

Table 1 Experimental design

	Experimental group	Control group
Prior to instruction	Data collection: pre-test (written; n=60)	Data collection: pre-test (written; n=59)
Lesson no. 1: Investigating the Seed Germination microworld	Instructional process: students investigate the microworld by working individually	Instructional process: same as in Experimental group
Lesson no. 2	Instructional process: Intervention—explicit instruction of MSK pertaining to the COV strategy	Instructional process: teaching about seed germination
Lesson no. 3	Instructional process: (1) Students investigate the microworld by working individually. (2) When students use unsound reasoning strategies teachers intervenes by making references to MSK pertaining to the COV strategy	Instructional process: (1) same as in Experimental group. (2) When students use unsound reasoning strategies teachers intervenes without making references to MSK pertaining to the COV strategy
Lesson no. 4 Investigating the 2nd microworld	Instructional process: (1) students investigate the 2nd microworld by working individually. (2) Teacher intervenes when students use unsound reasoning strategies	Instructional process: (1) same as in Experimental group. (2) When students draw invalid Inferences teachers intervenes without making references to MSK pertaining to the COV strategy
Lesson nos. 5–12 inquiry activities 1–8	Instructional process: (1) Inquiry learning activities—students work individually. (2) Teacher intervenes when students use unsound reasoning strategies	Instructional process: (1) same as in Experimental group. (2) When students use unsound reasoning strategies teachers intervenes without making references to MSK
Following lesson 12	Data collection: post-test (written; n=60)	Data collection: post-test (written; n=59)
Three months after lesson 12—delayed transfer (retention)	Data collection: students work individually on a new inquiry learning activity that tests delayed transfer (retention). Collecting written activity-sheets (n=60)	Data collection: same as in Experimental group. Collecting written activity-sheets (n=59)

total teaching time. We did not withhold any biological topic required in the curriculum, from neither the control nor the experimental group. In addition, both the control and the experimental group received instruction in 10 Inquiry tasks that were not part of the official curriculum. The experimental group received a second addition consisting of explicit teaching of MSK in the context of the control of variables strategy. Students in the control sub-groups received instead, and for the same amount of time, instruction about the scientific topics addressed by the inquiry tasks.

Ethical considerations regarding our research design may benefit by making an analogy to medical research. Ethical criticism of withholding treatment from control groups in research settings—primarily in the context of medical research—has focused on the practice of providing a placebo, i.e. a substance or procedure with no proven effect. Critics claim that the control group is thereby deprived of the standard medical care and its proven beneficial effect (Rothman and Michels 1994). Against this, it has been urged that we should distinguish the setting of medical research—where the objective is to obtain reliable information for future benefit—from the setting of providing medical care (Miller and Brody 2002). In any event, the most demanding position in the field of medical ethics would require that the control group be provided with the treatment that is standard-of-care in non-research settings. Drawing an analogy from the field of medical ethics to the field of educational research, the control group in our study was not deprived of the standard "treatment", i.e. instruction in the science curriculum, and in fact was even provided with a higher "standard of treatment", namely special inquiry tasks. Hence we see no basis for ethical concern. True, they were not provided with the additional intervention that was the focus of the study. But this can hardly be conceived as a deprivation, since the purpose of our investigation was to determine whether (and to what extent) this intervention yields additional benefits; hence such benefits cannot be posited in advance.

Tasks and instrumentation

Computerized tasks The computerized tasks used in this study are two simple computerized microworlds—the Seed Germination task and the Guinea-Pig task (Zohar 2004). These tasks are an adaptation of earlier tasks (Kuhn et al. 1992, 1995; Schuable 1990) that were initially designed to test inductive reasoning. The adaptation consisted of creating microworlds that have the same logical structure as the earlier microworlds, but whose topics match subjects from the grade 8 science curriculum.

The seed germination microworld In the seed germination microworld students are asked to investigate five variables: seed size, depth of sowing, size of earth particles, adding a fertilizer and disinfecting the seeds (see also Fig. 1). The computerized database includes data for 48 different combinations of variables: four variables with two values each (either causal or non-causal), and one variable with three values (two of which are causal and one of which is non-causal). Students need to determine which of these variables have a causal effect on germination rate, as measured by the percentage of germinating seeds. The outcome consists of four different germination rates (20, 40, 60 and 80%). The problem is formulated in terms of the need to find out which of the variables has a causal effect on the outcome. Students have to determine which of these variables have a causal influence on germination rate, as measured by the percentage of germinating seeds. Students' investigation consists of defining the variable(s) they wish to investigate, planning a combination of variables they wish to examine, examining the appropriate records on the computer, making inferences and justifying them.

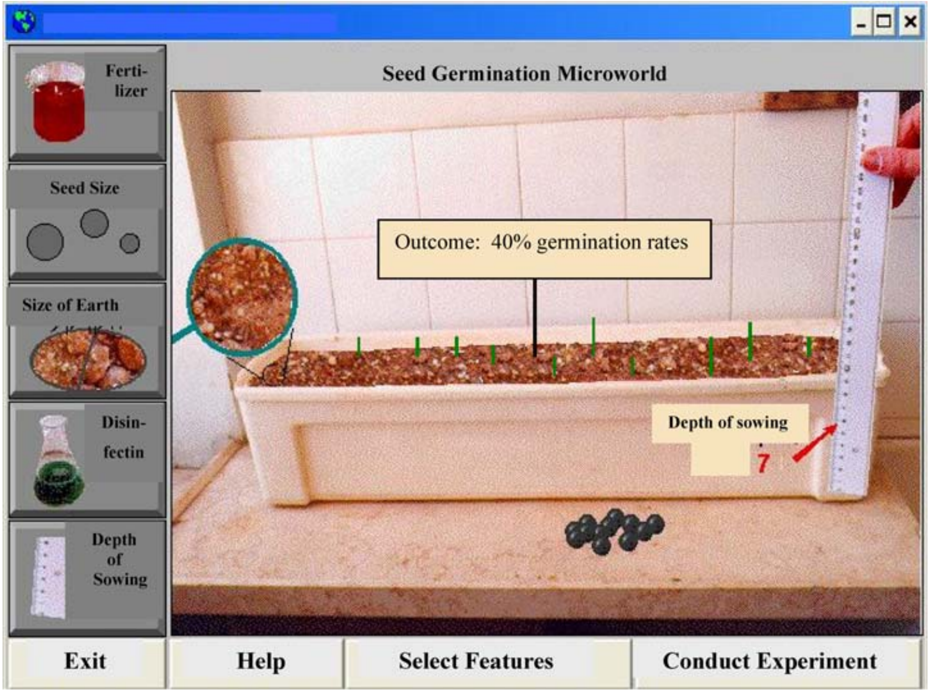


Fig. 1 Computer screen of the seed germination microworlds

The Guinea-pig microworld The Guinea-pig microworld consists of a different set of variables and outcomes, but its logical structure and computer interface are the same as in the seed germination task. Previous studies established the equivalence of the two tasks. The problem presented to students is framed as "finding out which of five features affects the weight of Guinea-pigs". The five variables are: caloric value, level of physical activity, the species of the guinea-pig, whether or not water is added to the food and source of carbohydrates (rice or pasta). The outcome is given in terms of the weight that the guinea-pig gains (0, 3, 6 and 10 g). Our previous studies confirmed the equivalence of the two microworlds in terms of their degree of difficulty.

Students' independent investigation of the microworld was governed by a Blank data table into which students were asked to enter the data of the computerized experiments they had conducted (Zohar and Aharon-Kravetsky 2005, see also Table 2). The data table was designed so that it would lead students through a fixed sequence of investigation. For each experiment with the computerized task, the blank data table thus requires students to write down the feature(s) they wish to investigate, the combination of variables they choose for the computerized experiment, the outcome of the experiment, the conclusion and its justification.

At the end of lessons 1 and 3, after students had completed at least 10 experiments, they handed-in the completed data tables which were then analyzed by the researchers (see below). The computerized tasks were used during the first four lessons in which the inquiry curriculum had been taught. The seed germination task was used in lessons 1–3, and the Guinea-pig task was used in lesson 4. Non-computerized inquiry tasks were used during lessons 5–12.

Table 2 Blank data table of the seed germination microworld

Experiment no.	The feature (s) you are investigating	Experimental conditions					Outcome	Conclusion	Justification
		Adding a fertilizer	Seed size	Size of earth particles	Disinfecting the seeds	Depth of sowing			

Children are given this blank table, in which they are asked to enter the data of the computerized experiments they conduct

Non-computerized tasks Inquiry learning activities, whose topics match subjects from the grade 8 science curriculum, consisted of written activity-sheets that include (among other things) questions addressing elements of MSK pertaining to variable control. Students were presented with various short stories about scientific experiments and were asked to determine whether or not they can draw an inference. Then they were further asked to justify their response. When students replied that they cannot draw an inference, they were asked to suggest an alternative, better experiment that would allow them to draw inferences and justify their experiment. For instance: Inquiry learning activity no.3 presented a story about Dan and Sharon who set out to investigate the effect of water on seed's respiration: Dan and Sharon knew that during respiration seeds absorb O_2 and release CO_2 and that in order to confirm respiration researchers can test the release of CO_2. Dan and Sharon therefore decided to use Phenol Red, an indicator that changes color (from red to yellow-orange) only in the presence of CO_2. The experiment they conducted is described in Table 3. Since only in tube no. 1 the color had turned yellow, Dan and Sharon concluded that only bean seeds are conducting respiration.

In the written activity-sheet students were asked to determine whether or not Dan and Sharon can draw a valid inference from this experiment. Then they were further asked to justify their response. When students replied that they cannot draw a valid inference, they were asked to suggest an alternative, better experiment that would allow them to draw inferences and to justify their experiment.

Treatment

The intervention consisted of explicit teaching of MSK that took place in the experimental group only. It is important to emphasize that by defining the treatment as "explicit" our aim is to articulate elements pertaining to MSK in an explicit way, but we do not mean to say

Table 3 Inquiry learning activity no. 3—Dan and Sharon's Experiment

Experimental conditions	Tube no. 1	Tube no. 2	Tube no. 3	Tube no. 4
Seed: bean/pea /wheat /chick-pea	bean	pea	chick-pea	Wheat
Phenol red: +/−	+	+	+	+
Water: +/−	+	_	_	_
Test tube: open/close	close	close	close	Close
Results	Color turn yellow	No change	No change	No change

that we adopted a model of instruction that is based on transmission of information. Rather, our model of "explicit" refers to instruction that focuses on providing experiences that will help students in constructing their own MSK regarding variable control. Therefore, teaching MSK is indeed the goal of the intervention, but teaching applies methods of knowledge construction rather than knowledge transmission. The intervention consisted of two parts: (a) A short unit of instruction of MSK that took place in the forum of an entire class (with approximately 30 students, for approximately 45 min). Students in the control group received instead, and for the same amount of time, a short unit of instruction about seed germination which is the content of the computerized microworld; (b) Probes given during individual students' engagement with the inquiry tasks.

The short unit of instruction focused on discussing various components of meta-strategic knowledge regarding the control of variables strategy. The teacher demonstrated an experiment in which she purposely failed to control variables. The teacher 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.

The second part of the intervention consisted of probes given to individual students during lessons 3–12 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 a lesson that applied inquiry task no.3 (see above p.12) the teacher diagnosed that Ben failed to apply the control of variables rule. Ben 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:

Teacher: Can we draw a valid conclusion?

Ben: No, because they [i.e., in the first, given experiment] did not control variables….. [but] I did control variables because I put the same things in each test tube.

Teacher: So can we draw a valid conclusion from your experiment?

Ben: Yes because there is control of variables

Teacher: Do you remember what we had learned from the experiment with the desk lamp?

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.

Teacher: Do you see any similarity between the desk lamp experiment and the experiment you suggested here?

Ben: It's the same thing.

Teacher: Is this what you did here? Used control of variables? [pointing to the table with the experimental design which Ben created]

Ben: Yes. Here you can see that I did everything… and here… [long pause]… here I…. I don't know…

Teacher: Think… Did you apply the control of variables rule?

Ben: Here… I think… I think I should have… Perhaps I should have used the same kind of seed in all test tubes…

Teacher: And then you will be controlling variables?

Ben: Yes, because then everything will be equal between the test tubes except for the water.

Teacher: So now you know what you need to do?

Ben: Yes… that everything will be the same and only one feature that I want to find out if it makes a difference then I change it from one to the other.

This transcript documents the gap between a student'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 to correct his mistake. Our assumption in this part of the intervention is that the teacher-student interaction affects the development of students' thinking and therefore it is considered part of the intervention. The above example shows however that it makes sense for the teacher to intervene only in the cases in which the teacher had detected students' errors, because when students do not make mistakes the teacher's guidance is not needed. Accordantly, the frequency of students getting probes is determined by their behaviors and not by an a priori decision about an optimal number of questions. We thus define the intervention as flexible in the sense that teachers scaffold students' thinking until they sense that scaffolding is no longer needed. This is an important point in terms of our data collection because although it may seem that different students received unequal treatment (because they got a different amount of teacher's guidance), our claim is that in fact they did receive an equal treatment in the sense that all students received scaffolding until it was no longer needed. Obviously, this part of the intervention was designed according to the ideas first put forward by Vygotsky (1978, 1934/1986) about the nature of flexible scaffolding.

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. The teacher responded to students' mistakes in the context of the biological topics of the inquiry learning activities which was the main teaching goal (as required from the science curriculum). The teacher asked a series of guiding questions such as: "Do you remember what we had learned in the last lesson?"; "Do you see any similarities between what we had learned and the problem you are investigating?"; "Are you using what we had studied in the previous lesson?" etc. The teacher also responded to students who made mistakes by making it clear that their answers are wrong (e.g., "Perhaps you should check your answer one more time"). She gave students feedback, encouraged them to keep trying (e.g., Please check your answer carefully), and gave them emotional support. However, in the control group the teacher did not give any feedback that related directly to the control of variables strategy. For instance: In inquiry learning no. 3 the teacher diagnosed that Sera failed to conduct an experiment. She asked her:

Teacher: Do you remember what we had learned last week?

Sera: Yes we had learned about seed germination and plants reproduction.

Teacher: Do you see any similarities between what we had learned and the problem you are investigating now?

Sera: Yes, it is about….what a seed needs for… so he will carry out respiration and grow.

Teacher: Are you using what we had studied in the previous lesson?

Sera: Yes, I know it needs water…but I am not sure what to put in here…

Teacher: Please check your answer carefully.

Sera: But I am not sure why the Phenol turns yellow only here?

Teacher: Perhaps you should check the experiment you conducted once again.

Data collection and analysis

A written test to assess students' ability to use variable control was given on two separate occasions: a pre-test that was given before the beginning of instruction, and a post-test that was given after the completion of instruction. The pre- and post-tests were equivalent in terms of their logical structure, but the contents of the fictitious story and of the scientific experiment differed in the two versions of the test. The written test consisted of two parts: Part 1 assessed strategic knowledge by means of three different items that required variable control. Students were presented with a fictitious story about a scientific experiment and asked (a) whether its conclusions are valid and, (b) to justify their response. They were also asked to plan an alternative experiment. Part 2 assessed meta strategic level by asking students to explain why they planned their experiment the way they did, to explain what are the differences between the given experiment and the new experiment they planned and to explain whether they can draw valid inferences from the new experiment, and if so why. The strategic level for each item was coded according to an adaptation of the coding scheme developed by Kuhn et al. (1992, 1995). The gist of the coding system is that variable control is a necessary condition for drawing a valid inference. In order for an inference to be judged valid, students needed to draw a conclusion that is based on at least two experiments, in which only one variable varied and all other variables remained constant. The strategic level for each answer scored as either 1 when students' responses included evidence for a valid inference or when students' responses did not include evidence for a valid inference. The total score of the strategic level for each student thus ranged between 0 and 3. Students' responses to the meta-strategic level were analyzed by using the coding scheme for MSK developed by Kuhn and Pearsall (1998). Each question thus received a score ranging between 0 and 6, and the total MSK score thus ranged between 0 and 18. The total MSK score was computed as the student's mean score for all three questions and thus also ranged between 0 and 6.

A written test to assess delayed transfer (retention) took place 3 months after the completion of instruction. The delayed transfer test was designed in a similar way to the inquiry learning activities. Once again students were presented with a novel fictitious story about a scientific experiment. Students were asked (among other things) to plan an experiment and were evaluated by judging whether or not their plan applied the control of variables rule. They were also asked to explain and to justify their plan. The strategic level was scored according to the same coding scheme developed by Kuhn et al. (1992, 1995). Scoring was either 1 (when students' responses included evidence for controlling variables) or 0 (when students' responses did not include such evidence). The meta-strategic level was analyzed by using the same MSK coding schemes (developed by Kuhn and Pearsall 1998) that we had used in the pre-and post-tests.

Inter-rater reliability was above 90% for all items.

Results

Analysis of data from written pre- and post-tests

Strategic level in written tests in the experimental and control groups

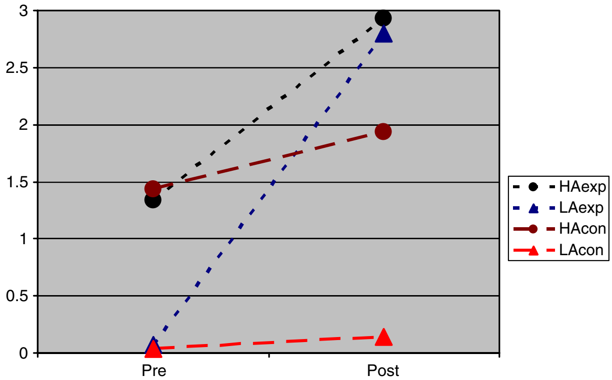
In the pre-test the experimental and control groups had similar scores and the small difference between them was not significant (Mexp=0.70, SD=0.92; Mcon=0.75, SD=0.97; $t(117)=-0.26$; $P>0.05$), indicating that before the intervention students from both groups demonstrated the same strategic level. In the post-test, 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 was conducted. The dependent variable was students' mean scores. The independent variables were time (pre-post, a within subject variable) and treatment (experimental vs control, a between subject variable). The findings showed (a) a significant main effect for time $F_{(1,117)}=188.44$; $P<0.001$, indicating a difference between the pre-test and post-test 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 meta-strategic intervention; (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.

Strategic level in written tests: differences between LA and HA students

Figure 2 presents the scores of the four sub-groups in the written pre-test and post-test. The graph shows that in the pre-test students from the two LA sub-groups 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 sub-groups 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 sub-groups was the same and the level of students from the two HA sub-groups was the same. Nevertheless, the pre-test 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; $t(65)=10.87$; $p<0.001$), indicating that before the intervention HA students demonstrated a higher strategic level than LA students.

Fig. 2 Strategic level in the 4 sub-groups: mean score of HA and LA students in pre-test and post-test (n=119)



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

To test the significance of the differences between means scores of the four sub-groups we conducted a 2×2×2 (treatment × student level × time) repeated measures ANOVA. The dependent variable was students' mean scores. The independent variables were time (pre-post, a within subject variable); treatment (experimental vs control, a between subject variable) and student level (a between subject variable). The findings showed (a) a significant main effect for treatment $F_{(1,115)}=100.03$; $p<0.001$, indicating the effect of the meta-strategic intervention; (b) a significant main effect for student level $F_{(1,115)}=163.43$; $P<0.001$, indicating differences between LA and HA students; (c) a significant interaction effect between treatment and student level $F_{(1,115)}=24.92$; $P<0.001$, indicating that the meta-strategic intervention affects LA and HA students differently. The interactions between time and treatment and between student level and time were also significant, as well as the triple interaction between treatment, student level and time.

Meta-strategic level in written tests in the experimental and control groups

In the pre-test the experimental and control groups had similar MSK scores and the small difference between them was not significant (Mexp=1.83, SD=1.70; Mcon=1.84, SD=1.69; $t(117)=-0.02$, $P>0.05$), indicating that before the intervention students from both groups demonstrated the same meta-strategic level.

In the post-test, the mean score of the experimental group (M=5.51, SD=1.21) was higher than the mean score of the control group (M=2.42, SD=2.09). A repeated measures ANOVA was conducted. The dependent variable was students' mean MSK scores. The independent variables were time (pre-post, a within subject variable) and treatment (experimental vs control, a between subject variable). The findings showed (a) a significant main effect for time $F_{(1,117)}=172.65$; $P<0.001$, indicating a difference between the pre-test and post-tests in the mean score of all students; (b) a significant main effect for treatment

$F_{(1,117)}$=33.00; $P<0.001$, indicating the effect of the meta-strategic intervention; (c) a significant interaction effect between time and treatment $F_{(1,117)}$=91.68; $P<0.001$, indicating that the gain of students in the experimental and control groups was different across time.

Meta-strategic level in written tests: differences between LA and HA students

Figure 3 presents the MSK scores of the four sub-groups in the written pre-test and post-test. The graph shows that in the pre-test the MSK scores of students from the two LA sub-groups were similar and the small difference between them was not significant (Mexp=0.67, SD=0.52; Mcon=0.71, SD=0.50; $t(57)=-0.26$; $P>0.05$). The MSK scores of students from the HAexp and HAcon sub-groups were also similar and the small difference between them was not significant (Mexp=3.00, SD=1.69; Mcon=2.94, SD=1.73; $t(58)=0.12$; $P>0.05$), indicating that prior to the intervention the meta-strategic level of students from the two LA sub-groups was the same and that the meta-strategic level of students from the two HA sub-groups was the same. On the other hand, the mean score (combined from the MSK scores of students in the experimental and the control groups) of the HA students (M=2.97, SD=1.69) was significantly higher than the mean score (combined from the MSK scores of students in the experimental and the control groups) of the LA students (M=0.69, SD=0.50; $t(69)=9.94$; $p<0.001$), indicating that before the intervention HA students demonstrated a higher meta-strategic level than LA students.

In the post-test, students from three sub-groups (HAexp, LAexp and HAcon) made considerable progress compared with their pre-test scores. Students from the LAcon group made no progress. The post-test score of HAexp students (M=5.76, SD=0.89) is higher than the post-test score of HAcon students (M=3.93, SD=1.88). However, A larger gap is found between the post-test score of LAexp students (M=5.25, SD=1.44) and LAcon students (M=0.86, SD=0.68). Moreover, the post-test score of LA students from the experimental group is higher than the score of HA students from the control group, and close to the score of the HA students from the experimental group. Therefore, the data show that the largest pre-test to post-test gain in MSK scores was for LA students in the experimental group.

To test the significance of the differences between the mean MSK scores of the four sub-groups we conducted a 2×2×2 (treatment×student level×time) repeated measures ANOVA. The dependent variable was students' mean MSK scores. The independent variables were

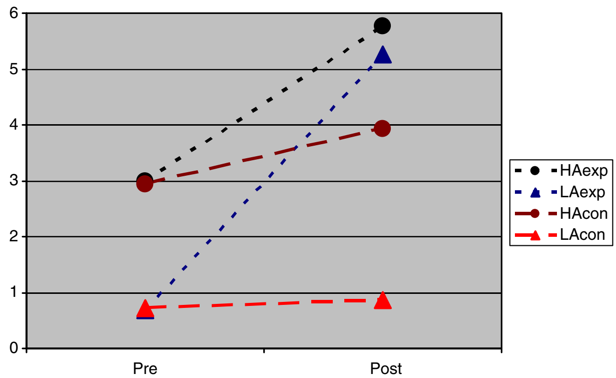


Fig. 3 Meta strategic level in the 4 sub-groups: mean score of HA and LA students in pre-test and post-test (n=119)

time (pre-post, a within subject variable) treatment (experimental vs control, a between subject variable) and student level (a between subject variable). The findings showed (a) a significant main effect for treatment $F_{(1,115)}=71.83$; $P<0.001$, indicating the effect of the meta-strategic intervention; (b) a significant main effect for student level $F_{(1,115)}=121.83$; $P<0.001$, indicating differences between LA and HA students; (c) a significant interaction effect between treatment and student level $F_{(1,115)}=11.22$; $P=0.001$, indicating that the meta-strategic intervention affected LA and HA students differently. The interactions between time and treatment were also significant, as well as the triple interaction between treatment, student level and time.

Analysis of data from written delayed transfer (retention) test

Strategic level in written delayed transfer test (retention) in the experimental and control groups

In the delayed transfer test strategic scoring was either 1 (when students drew a valid inference) or 0 (when students did not draw a valid inference). The dependent variable was students' DT (delayed transfer) scores. The independent variables were treatment (experimental vs control). 95% of the students from the experimental group drew a valid inference compare to 18.6% of the students from the control group. A chi-square test showed that the difference between the experimental and control groups was statistically significant ($\chi^2=70.82$; $p<0.000$). These findings indicate that the effect of the meta-strategic intervention was preserved for 3 months after the completion of instruction.

Strategic level in written delayed transfer test (retention)—differences between LA and HA students

Figure 4 presents the scores of the four sub-groups in the delayed transfer test. The data show that 100% of the HAexp students drew a valid inference, compared to 90% of LAexp; 36.7% of HAcon; and 0% of the LAcon students. A chi-square test showed that the differences between the four sub-groups ($\chi^2=79.53$; $p<0.000$) were statistically significant. An additional set of tests to locate the significant differences among the various groups showed: (a) a significant difference ($\chi^2=27.80$; $p<0.000$) between HAexp and HAcon; (b) a significant difference ($\chi^2=18.37$; $p<0.000$) between LAexp and HAcon; (c) a significant difference ($\chi^2=48.12$; $p<0.000$) between LAexp and LAcon; (d) a significant difference ($\chi^2=13.07$; $p<0.000$) between HAcon and LAcon. However, the difference between HAexp and LAexp was not statistically significant ($\chi^2=3.15$; $p>0.05$). These findings indicate that the effect of the treatment was preserved for 3 months after the end of instruction.

Meta-strategic level in written delayed transfer (retention) test in the experimental and control groups

In the delayed transfer test the MSK score of the experimental group ($M=5.82$, SD=0.77) was higher than the MSK score of the control group ($M=2.95$, SD=2.23). These differences were statistically significant ($t_{(71)}=9.31$; $P<0.001$). The findings show that the effect of the meta-strategic intervention on students' meta-strategic thinking level was preserved for 3 months after the end of instruction.

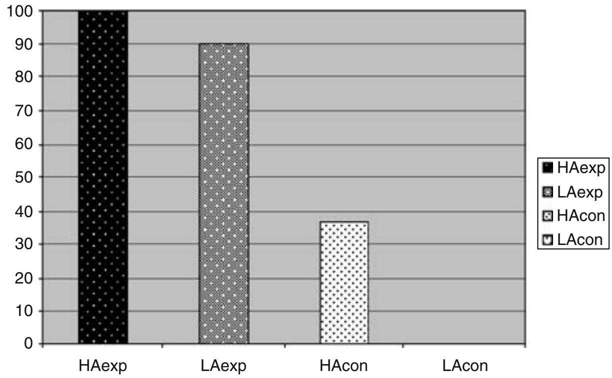


Fig. 4 Strategic level in the 4 sub-groups: percentage of students who drew a valid inference in delayed transfer test (n=119)

Meta-strategic level in written delayed transfer test (retention)—differences between LA and HA students

Figure 5 presents the MSK scores of the four sub-groups in the delayed transfer test. The data show that HAexp (M=6, SD=0) scored highest of all sub-groups followed by LAexp (M=5.63, SD=1.06) who scored higher than the HAcon (M=4.80, SD=1.34) and much higher than the LAcon (M=1.03, SD=1.01). To test the significance of the differences between MSK means score of the four sub-groups in the delayed transfer test (retention) we conducted a Two-way ANOVA. The analysis revealed (a) a significant main effect for treatment $F_{(1,115)}$=250.62; p<0.001, indicating that the effect of the meta-strategic treatment on students' meta-strategic thinking was preserved 3 months after the completion of instruction; (b) a significant main effect for student level $F_{(1,115)}$=127.26; P<0.001, indicating differences between LA and HA students; and, (c) a significant interaction effect between treatment and student level $F_{(1,115)}$=86.10; P<0.001, indicating that the different effect of the treatment for students' meta-strategic level was preserved for 3 months after the end of instruction.

Conclusions and discussion

The goal of the present study was to examine how explicit instruction of MSK that is mediated by verbal discussion, combined with multiple opportunities to practice the use of the control of variables strategy in an authentic school environment affects students'

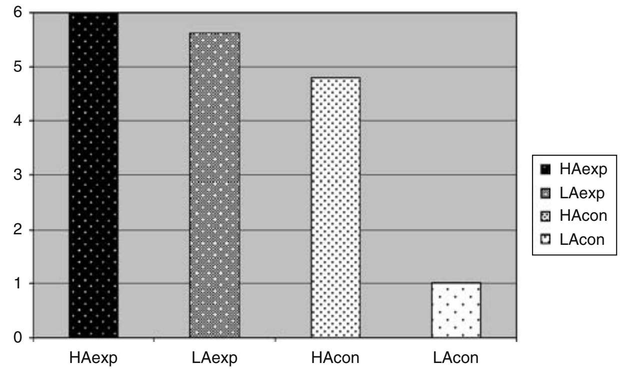


Fig. 5 Meta strategic level in the 4 sub-groups: mean score of HA and LA students in delayed transfer test (n=119)

strategic and meta-strategic levels of thinking. The findings showed a significant difference between the experimental and control groups on both the strategic and the meta-strategic levels of thinking. These findings support our first hypothesis according to which students in the experimental group would make more progress than students in the control group. These findings support previous studies showing the effect of teaching explicit knowledge regarding the control of variables thinking strategy (Chen and Klahr 1999; Ross 1988; Toth et al. 2000; Klahr and Nigam 2004). They also support the findings from the previous study conducted in our own research group (Zohar and Peled 2007) that was conducted in controlled laboratory conditions. In that study we assessed the effects of explicit teaching of meta-strategic knowledge (MSK) on gains of low-achieving (LA) and high-achieving (HA) 5th grade students (n=41). The results from the laboratory conditions study are parallel to the results of the present study. Namely, significant gains in reasoning scores of students from the experimental group (compared to students from the control group) were obtained on the strategic level and on the meta-strategic level. Significant gains were preserved in far transfer tasks 3 months after the end of instruction. Explicit teaching of MSK affected both LA and HA students, but it was extremely valuable for LA students. The fact that similar effects to the ones that had been obtained in the "sterilized" laboratory conditions were also obtained in the "messy" conditions that exist in an authentic school setting and in real classrooms, are encouraging and pave the way to wide scale implementation.

The ability to transfer knowledge to novel problems and to retain this ability for extended periods requires a substantial degree of understanding. In this study we have used assessment that took place 3 months after the completion of instruction and therefore assessed a delayed transfer (retention). This assessment showed significant differences between the experimental and control groups on both the strategic and the meta-strategic levels of thinking. We may therefore conclude that the experimental group students seemed to develop understanding of the control of variables strategy rather than to simply rote-learn how to solve the task they had engaged in during the intervention.

In our study gains were obtained in students' strategic level and in their meta-strategic level. Nelson and Narens (1994) describe a two-way feedback between the object level and the meta-level of thinking. Reasoning that takes place in the object-level, affects the meta-level, but then reasoning that takes place in the meta-level affects the way we think and act at the object level. More specifically, in a study that examined meta-strategic knowledge and strategic performance Kuhn and Pearsall (1998) raise several hypotheses regarding the relationships between these two levels of thinking and state that the direction of causality between these two levels is not clear: perhaps strategic success or strategic failure leads to greater meta-strategic awareness, perhaps meta-strategic understanding leads to better strategic performance, or perhaps each of these two levels had a necessary-but-not sufficient "gatekeeper" relation of one to the other. In the present study it was precisely the explicit teaching of MSK that triggered the development of thinking for students in the experimental group. We can therefore deduce that it was indeed the meta-strategic knowledge that caused the development we had witnessed in students' strategic performance. Although developmental changes and changes that follow explicit instruction may take on different routes, this conclusion provides empirical evidence that changes that take place on the meta-strategic level *can* in principle initiate changes on the strategic level.

Our findings are relevant for the on-going and lively discussion that currently takes place between two prominent teams of researchers: Klahr and Nigam (2004) who have made a case for the superiority of direct instruction over discovery learning in students' mastery of the control-of variables strategy, and Dean and Kuhn (2007) who followed students' mastery of the control of variables strategy over a time period of almost 6 months across varied content. Dean and Kuhn criticize Klahr and Nigam (2004) for their conclusion that direct instruction is preferable to discovery learning, on the ground that they did not assess delayed transfer. Dean and Kuhn show that directly following instruction, the group who received direct instruction indeed had an advantage over other groups. However, this advantage was not preserved 6 months after instruction. At that time students who had engaged the task without any intervention, thereby experiencing discovery rather than guided learning, outperformed all other groups. Dean and Kuhn thus conclude that direct instruction appears to be neither a necessary nor a sufficient condition for robust acquisition, transfer and maintenance of the control of variables strategy over time. These researchers therefore conclude that discovery learning is the most desired type of learning for the purpose of achieving long-term and transferable effects.

The learning experience that these researchers call "discovery learning" is in effect very similar to the learning experience of the control group in the present article because the control group students engage in an independent investigation of tasks requiring the control of variables strategy. The learning experience that these researchers call "guided learning" is in effect a form of explicit teaching of MSK because it consists of explicit verbal communication of general knowledge regarding the control of variables strategy. Therefore, the present study addresses similar issues to the ones addressed by Klahr and Nigam (2004) and by Dean and Kuhn (2007) adding a new aspect to their ongoing discussion because according to our findings the effects of explicit teaching did indeed foster a long-term and transferable effect.

We suggest that the way to resolve these seemingly contradictory findings is to unpack the terms "direct instruction", "guided learning" and "explicit instruction of MSK" by a detailed analysis of the specific pedagogies applied in each study. Rather than speaking only about direct instruction versus discovery learning, educators should look at a continuum of possible ways of instruction, and particularly ask what does the guided learning consist of. One end of this continuum consists of teachers who "transmit" knowledge and students who are passive recipients of knowledge. Direct instruction is close to this pole of the continuum. The other pole of this continuum consists of students who construct their own knowledge in an active way. Discovery learning is one of several teaching methods that are close to this end of the continuum. However, there are also many additional points along that continuum which may consist of different combinations of the methods that characterize each pole.

The instructional unit described in the present study indeed consisted of guidance regarding MSK. However, we made a great effort not to "transmit" the knowledge involved, but to coach students in a comprehensive process of knowledge construction rather than to "rote learn" the pertinent body of knowledge. Although this approach is reflected in our short unit of instruction that took place in the forum of the whole class, it is even more pronounced in part B of our intervention that consisted of probes, or individual coaching that students received during the practice sessions whenever they had failed to use the control of variables strategy. In effect, this part of our intervention had many of the characteristics of "guided discovery" because students were in general provided with multiple opportunities to discover correct thinking strategies while experimenting on their own, but also received opportunities for guidance from the teacher.

We therefore suggest that the resolution of the seeming contradiction among the studies discussed above may be located in the very different meaning of "treatment" or "instruction" in each of the studies. The closer instruction is to "transmission" pole, the less effective it would be in terms of long-lasting and transferable outcomes. The closer instruction is to the "knowledge construction" pole, it would have more long-lasting and transferable effects. The findings of Dean and Kuhn (2007) indeed show that discovery learning is preferable to guided instruction. However, it seems that this finding refers to guided instruction that would not be mapped close to the knowledge-construction pole. In contrast, the findings of the present study (in which the guided instruction was conducted in a form that is indeed close to the knowledge construction pole) show that discovery learning is less effective than guided learning.

In sum, this discussion has two important implications. From an educational practical point of view it emphasizes that not all explicit or guided teaching of MSK indeed has transferable and long-term effects. In order to obtain such effects it is imperative that the guided teaching will be conducted by methods of knowledge construction.

The pedagogies applied in the present study consisted of explicit instruction of MSK that was mediated by verbal discussion, combined with multiple opportunities to practice the use of the control of variables strategy across time, coupled with individual teacher–student interactions. Thus, instruction actually combines both a Piagetian component and a Vigotzkian one. The strong linguistic component that is a key part of our pedagogical way for teaching MSK is related to Vygotsky's theory (Vygotsky 1978, 1934/1986) that value social interaction, with language used as the 'tool' to negotiate meaning and extend knowledge. It is also related to Vygotsky's term "zone of proximal development" (ZPD). Rogoff (1990, 1994) extends Vigotzky's ideas by stressing the importance of explicit face-to-face social interaction in guided participation. Rogoff's ideas relate to the social constructivist theme of negotiating meaning where the dialogue serves several functions among which is helping the learner to test and refine ideas, introducing multiple perspectives, and negotiating limits on idiosyncratic conceptions (Duffy and Cunningham 1996).

The second crucial part of our pedagogical way for teaching MSK is the students' concrete experiences in which they *use* a thinking strategy rather then address it only in an abstract way. The "practical experiences" component is base on Piaget's theory (1948/1974) about the use of concrete experience in order to actively construct knowledge.

However, the present findings are not informative in determining the relative significance of each of these factors, the "linguistic component" and the "practical experiences" for they were all applied together. For practical educational purposes it may be important to discern the components of the educational intervention and to evaluate their relative contribution for students' reasoning gains. Future studies that will compare outcomes of various intervention sequences, will enable researchers to elaborate their understanding of the optimal components of explicit instruction of MSK that would achieve long-term and transferable effects.

Our third hypothesis, namely that LA students will benefit from the treatment more than HA students could not be fully tested in the present study because of a ceiling effect. One of the limitations of our study is that in all the measures we used, HAexp students eventually reached (or nearly reached) the highest possible scores, while LAexp students scored less high (even though the difference between the two groups was sometimes negligible). Since HAexp students were more affected by the ceiling effect than LAexp students we cannot make a valid comparison between the gains of students from the two experimental sub-groups. This calls for future research with a more difficult task that would avoid the problem of a ceiling effect. Nevertheless, the results clearly show that the performance of LA students in the experimental group improved in a dramatic way, as can be seen by the significant differences between LAexp and LAcon groups, and by the fact that the mean scores of the LAexp sub-group were mostly higher than the mean scores of the HAcon sub-group. Therefore, even though we cannot compare between LA and HA students, we can conclude that explicit teaching of MSK is an extremely valuable teaching strategy for students with low academic achievements. This conclusion is in line with prior research in both science and mathematics education showing that metacognitive instruction was 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; Mevarech and Fridkin 2006; Zohar and Peled 2007). This conclusion has two practical implications. First, it carries a clear recommendation stating that it is indeed valuable to apply explicit instruction of MSK for teaching thinking to LA students. Second, as explained earlier, teachers often do not believe that instruction of higher order thinking is an appropriate educational goal for LA students (Zohar et al. 2001; Raudenbush et al. 1993; Warburton and Torff 2005). One common reason for this conviction relates to a lack of satisfactory instructional means for teaching thinking to LA students. A report of our findings, combined with a discussion of the instructional methods used in this study, may be used in professional development programs for helping teachers to overcome their initial doubts as to whether or not teaching thinking to LA students is an appropriate educational goal. In addition it will also provide them with a practical teaching strategy for achieving this goal.

Our study has two further limitations. First, this study addressed only one thinking strategy. In order to be able to generalize from the findings, we are currently conducting a similar study addressing two additional thinking strategies (formulating a research question and formulating hypotheses). Second, the present study cannot shed much light on the interactions between the strategic and meta-strategic levels and their influence on the development of students' thinking. In addition, this study reports quantitative findings only and therefore cannot inform us about the *change processes* that take place following the explicit instruction of MSK or regarding the *change processes* that took place during student-teacher interactions. In order to overcome these limitations we are currently conducting two detailed and thorough qualitative analysis of the data we collected as part of the present study. One of the qualitative analysis focuses on the *process of change* that takes place following explicit teaching of meta-strategic knowledge. In this analysis we are looking at the score of each student at the strategic and at the meta-strategic level across all inquiry sessions. Then we draw a developmental pattern for each student, and group students with similar patterns into the same group. Preliminary findings from this analysis: (a) unveil six recurring learning patterns characterizing the change processes that take place following the MSK intervention; (b) portray the dynamics of the interrelations between the strategic and the meta-strategic level; and, (c) portray the interactions between students' minds and the educational intervention.

The second qualitative analysis focuses on *case-study* analysis using a narrative approach. This lengthy narrative analysis provides a detailed description of the verbal discussions and interactions that take place between the teacher and individual students. Preliminary findings show several directions of the relationships between the strategic and the meta-strategic level: Apparently, not in all cases it was the meta-strategic level that affected strategic performance. In some cases it was strategic success or strategic failure that led to greater meta-strategic awareness. This finding is in line with Kuhn and Pearsall's (1998) previous study (mention earlier), which claims that the main feature of the relationships between the strategic level and the meta-strategic level is that they "feed back" each other, namely, that change in one level leads to change in the other levels and so on.

Furthermore, the narrative analysis showed that in the cases of some LA students construction of meta-strategic knowledge took place during verbal interactions between the teacher and individual students, highlighting the significance of such interactions for the learning process of LA students (Vygotsky 1934/1986).

In addition, the transition from meta-strategic knowledge regarding specific variables to general meta-strategic knowledge (entailing generalizations of rules) was found to be a crucial stage in the acquisition of strategic knowledge. For some students this stage did not take place spontaneously. This finding implies the need to address this transition in an explicit way in the course of instruction.

In sum, Meta-strategic Knowledge was found in our study as a promising and fruitful "tool" for bringing about change in students' strategic and meta-strategic levels of thinking. In particular explicit teaching of MSK was identified as an invaluable instructional means for supporting the progress of students with low academic achievements. Therefore our findings imply that explicit teaching of Meta-strategic Knowledge should become an inseparable component of teaching thinking and it should be at the focus of further educational studies.

References

Cardelle-Elawar, M. (1995). Effects of teaching metacognitive skills to students with low mathematics ability. *Teaching and Teacher Education*, *8*, 109–121.

Chen, Z., & Klahr, D. (1999). All other thing being equal: Children's acquisition of the control of variables strategy. *Child Development*, *70*, 1098–1120.

Dean, D., & Kuhn, D. (2007). Direct instruction vs. discovery: The long view. *Science Education*, *91*, 384–397.

Duffy, T. M., & Cunningham, D. J. (1996). Constructivism: Implications for the design and delivery of instruction. In D. H. Jonassen (Ed.) *Handbook of research for educational communications and technology* (pp. 170–198). New York: Simon Schuster Macmillan.

Flavell, J. H., Miller, P. H., & Miller, S. A. (2002). *Cognitive development* (4th Edn.th ed.). Upper Saddle River, New Jersey: Prentice Hall.

Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: effects of direct instruction and discovery learning. *Psychological Science*, *15*, 661–667.

Kramarski, B., Mevarech, Z. R., & Arami, M. (2002). The effects of metacognitive instruction on solving mathematical authentic tasks. *Educational studies in mathematics*, *49*, 225–250.

Kuhn, D. (1999). Metacognitive development. In L. Balter, & C. S. Tamis-LeMonda (Eds.) *Child psychology, a handbook of contemporary issues*. Ann Arbor, MI: Taylor and Francis.

Kuhn, D. (2000). Why development does (and doesn't) occur: Evidence from the domain of inductive reasoning. In R. Siegler, & J. McClelland (Eds.) *Mecahnisms of cognitive development: Neural and behavioral perspectives*. Mahwah, NJ: Erlbaum.

Kuhn, D. (2001a). How do people know? *Psychological Science*, *2001*, 1–8.

Kuhn, D. (2001b). Theory of mind, metacognition and reasoning: A life-span perspective. In H. Hartman (Ed.) *Metacognition in Learning and Instruction* (pp. 301–326). Netherlans: Kluwer.

Kuhn, D., Black, J., Keselman, A., & Kaplan, D. (2000). The development of cognitive skills to support inquiry learning. *Cognition and Instruction*, *18*, 495–523.

Kuhn, D., Garcia-Mila, M., Zohar, A., & Anderson, C. (1995). Strategies of knowledge Acquisition. To be printed in: *Monographs of the Society for Research in Child Development (MSRCD)*.

Kuhn, D., Katz, J., & Dean, D. (2004). Developing Reason. *Thinking & Reasoning*, *10*, 197–219.

Kuhn, D., & Pearsall, S. (1998). Relations between metastrategic knowledge and strategic performance. *Cognitive Development*, *13*, 227–247.

Kuhn, D., Schauble, L., & Garcia-Mila, M. (1992). Cross- domain development of scientific reasoning. *Cognition and Instruction*, *9*(4), 285–327.

Mevarech, Z. R. (1999). Effects of metacognitive training embedded in cooperative settings on mathematical problem solving. *Journal of Educational Research*, *92*(4), 195–205.

Mevarech, Z. R., & Fridkin, S. (2006). Who benefits from IMPROVE? The differential effects of IMPROVE on mathematical knowledge and reasoning. School of Education, Bar- Ilan University, Israel. Paper presented at SIG16 Metacognition Conference, Cambridge, UK. July 2006.

Mevarech, Z. R., & Kramarski, B. (1997). IMPROVE: A multidimensional method for reaching mathematics in heterogeneous classrooms. *American Educational Research Journal*, *34*, 365–394.

Millar, R., & Osborne, J. (1998). *Beyond 2000; Science education for the future*. London: King's College.

Miller, F. G., & Brody, H. (2002). What makes placebo-controlled trials unethical? *American Journal of Bioethics*, *2*(2), 3–9.

Nelson, T. O., & Narens, L. (1994). Why investigate metacognition? In J. Metcalfe, & A. P. Shimamura (Eds.) *Metacognition: knowing about knowing, chapter 1* (pp. 1–26). Cambridge, MA: The MIT press.

Pearsall, S. (1999). Effects of metacognitive exercise on the development of scientific reasoning. Unpublished doctoral dissertation, Teachers College, Columbia University, New York.

Piaget, J. (1948/1974). *To understand is to Invent: The future of education*. New York: Viking.

Qualifications and Curriculum Authority (retrieved July 2005). *Science for public understanding*. http://www.qca.org.uk/index.html.

Raudenbush, S. W., Rowan, B., & Cheong, Y. F. (1993). Higher order instructional goals in secondary schools: Class, teacher and school influences. *American Educational Research Journal*, *30*(3), 523–553.

Resnick, L. (1987). *Education and learning to think*. Washington D.C.: Natioanl Academy Press.

Rogoff, B. (1990). *Apprenticeship in thinking: Cognitive development in social context*. New York: Oxford University Press.

Rogoff, B. (1994). Developing understanding of the idea of communities of learners. *Mind, Culture, and Activity*, 1(No. 4), Fall 1994.

Ross, J. A. (1988). Controlling variables: a meta-analysis of studies. *Review of Educational Research*, *58*(4), 405–437.

Rothman, K. J., & Michels, K. B. (1994). The continuing unethical use of placebo controls. *New England Journal of Medicine*, *331*, 394–398.

Rutherford, F. J., & Ahlgren, A. (1990). *Science for all Americans*. New York and Oxford: Oxford University Press.

Schraw, G. (1998). Promoting general metacognitive awareness. *Instructinal Science*, *26*, 113–125.

Schuable, L. (1990). Belief revision in children: The role of prior knowledge and strategies for generating evidence. *Journal of Experimental Child Psychology*, *49*, 31–57.

Teong, S. K. (2003). The effect of metacognitive training on mathematical word-problem solving. *Journal of Computer Assisted Learning*, *19*(1), 46–55.

Toth, E. E., Klahr, D., & Chen, Z. (2000). Bridging research and practice: A cognitively based classroom intervention for teaching experimentation skills to elementary school children. *Cognition and instruction*, *18*(4), 423–459.

Veenman, M. V. J., Van Hout-Wolters, B., & Afflerbach, P. (2006). Metacognition and learning: conceptual and methodological considerations. *Metacognition Learning*, *1*, 3–14.

Vygotsky, L. (1934/1986). *Thought and language (Rev. ed)*. Cambridge, MA: MIT Press.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. In M. Cole, V. John-Steiner, S. Scribner, & E. Souberman (Eds. & Trans.). Cambridge, MA: Harvard University Press.

Warburton, E., & Torff, B. (2005). The effect of perceived learner advantages on teachers' beliefs about critical-thinking activities. *Journal of Teacher Education*, *56*, 24–33.

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling and metacognition: making science accessible to all students. *Cognition and Instruction*, *16*(1), 3–118.

White, B. Y., & Frederiksen, J. R. (2000). Metacognitive facilitation: An approach to making scientific inquiry accessible to all. In J. L. Minstrell, & E. H. Van-Zee (Eds.) *Inquiry into Inquiry learning and teaching in science* (pp. 331–370). Washington D.C: American Association for the Advancement of Science.

Zohar, A. (2004). *Higher order thinking in science classrooms: Students' learning and teacher' professional development*. The Netherlands: Kluwer Academic Press.

Zohar, A., & Aharon-Kravetsky, S. (2005). Exploring the effects of cognitive conflict and direct teaching for students of different academic level. *Journal of Research in Science Teaching*, *42*, 829–855.

Zohar, A., & Peled, B. (2007). The effects of explicit teaching of metastrategic knowledge on low- and high-achieving students. *Learning and instruction*, in press (September 19).

Zohar, A., Vaaknin, E., & Degani, A. (2001). Teachers' beliefs about low achieving students and higher order thinking. *Teaching and Teachers' Education*, *17*, 469–485.