Science Education International
Vol. 16, No. 1, March 2005, pp. 23-38

International Council of Associations in Science Education

The Essence of Open-Inquiry Teaching

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ABSTRACT *The Biomind program is a pilot project in Israeli high schools in which eleventh- and twelfth-grade biology students are trained to conduct an open inquiry. This paper describes a follow-up study of Israeli high school teachers who implemented this challenging and open-inquiry curriculum. During this follow-up, several participating teachers conducted authentic open inquiry, formulated several logically related questions, wrote a proposal, and conducted an experiment. The difficulties that the teachers encountered during their inquiry process were similar to those that their students encountered in conducting an open inquiry. These difficulties served as a basis for the design and implementation of workshops in which the participating teachers suggested techniques to help students successfully conducting an open inquiry. In addition, the results indicated that the workshops improved both teachers' understanding of the essence of the open inquiry process and teachers' pedagogical knowledge in teaching an open inquiry.*

KEY WORDS: *open inquiry, inquiry teaching, pedagogical knowledge, professional development.*

Introduction

Difficulties in Inquiry Teaching

The importance of engaging students in inquiry-based learning is a major issue in science education. In particular, inquiry-based learning is highly important to the understanding of the nature of science (Abd-El-Khalick, Bell, & Lederman, 1998). Teachers have a critical role in implementing inquiry-based learning, especially in the case of open inquiry (Bybee & Loucks-Horsley, 2001). The American National Science Education Standards (National Research Council [NRC], 1996) emphasizes the critical role of teachers in open inquiry learning. This role incorporates guiding, focusing, challenging, and encouraging students to engage in this kind of activity. The move from teachers who direct students in a structured inquiry to those who facilitate students in an open inquiry is a challenging endeavor for teachers to follow (Windschitl, 2002) and requires greater flexibility on the part of both teachers and students (Zion et al., 2004b).

There are many difficulties in implementing the open-inquiry teaching approach among science teachers. Bybee and Loucks-Horsley (2001) indicated that "*Teachers need to know science as deeply, even more deeply, than their students*" (p. 4). Lack of content and procedural knowledge requires an academic support system for the teacher in order to fill in the gaps. In addition, academic support is needed to help science teachers to understand that science is a discipline with uncertainties that provides room for human innovation and debate (Hogan & Berkowitz, 2000). Teachers, who lack experience in conducting authentic research, often have difficulties in using inquiry-based teaching in their classes (Lee, Hart, Cuevas, & Enders, 2004; Windschitl, 2002). Windschitl (2002) also refers to difficulties arising from teachers' attitudes and beliefs:

> "*Most science teachers view inquiry as difficult to manage, and believe that inquiry instruction is possible only with above average students. Science teachers may be confused about what constitutes inquiry. Teachers may believe in a universal stepwise procedure, 'The Scientific Method', for doing science, thus dismissing the creative and imaginative nature of the scientific endeavor. Teachers form individualized conceptions of inquiry, and employ these for science teaching in ways that may not match the conceptions of researcher*" (pp. 115-116).

Teachers, who lack experience in conducting authentic research, lack an understanding of inquiry procedural knowledge. They do not understand the sequence of events in the inquiry process (Windschitl, 2002). In addition, teachers often have difficulty in moving from a mechanical teaching approach, in which they see a simple series of events in experimenting, to "mastery" teaching, in which they understand the content, concepts, and processes of science (Vasquez & Cowan, 2001). Teachers who provide inquiry-based instruction tend to have difficulty in finding appropriate inquiry topics for high school students of different backgrounds and ability levels (Trautmann, Avery, Krasny, & Cunningham, 2002). Thus, helping teachers learn how to facilitate students in autonomous open inquiry is a way to enhance teachers' professional development.

An Open Inquiry-based Course for Teachers

There are different ways to assist teachers in overcoming difficulties in teaching and in enhancing their professional development. Vasquez and Cowan (2001) listed a series of actions that hold implications for teachers' practice. Reflection, self-examination, peer study groups, mentoring by master-level teachers, and time for developing a deeper understanding of the content and pedagogical knowledge of the curriculum. Engaging teachers in curriculum development and development of teaching activities is another way to help teachers in overcoming their difficulties (Parke & Coble, 1997). In addition, teachers' professional development is enhanced when teachers evaluate and practice new teaching activities in collaboration with their colleagues (Andrews & Lewis, 2002; Bell, 1998; Hogan & Berkowitz, 2000; Sandholtz, 2002).

An inquiry-based course for teachers is a useful tool for science education as a way to identify problems and enhance the professional development of teachers (Bell, 1998; Crockett, 2002; Hogan & Berkowitz, 2000). Teachers who take a science course in which they learn scientific topics through inquiry are able to share the same opportunities with their students in developing an understanding of the nature of science (NOS) and the essence of scientific inquiry (Lederman & Lederman, 2004; NRC, 1996). Luft (2001) monitored teachers who experimented with both structured and guided inquiry-based learning. Teachers were provided with the theoretical background of the inquiry process and then conducted extended inquiry by themselves. This inquiry followed the same process that students usually experienced, but teachers received continuous support and feedback from program staff and peers. Thus, teachers combined theoretical aspects of inquiry-based learning with practical approaches in teaching inquiry (Luft, 2001; Parke & Coble, 1997; Radford, 1998). In contrast to structured inquiry, an open inquiry is more difficult to manage. In addressing this issue, Hogan and Berkowitz (2000) suggested that during the practical open inquiry course for teachers, both teachers' and their students' difficulties in conducting an inquiry-based autonomous project should be effectively identified and monitored. Furthermore, both the participating teachers themselves and science educators who analyzed teachers' inquiry performances are ideally suited to formulate suggestions for overcoming difficulties in performing an open inquiry process. The current research used Hogan and Berkowitz's (2000) model, and monitored teachers who were involved in implementing the "Biomind" curriculum (program).

The Biomind Program

The Biomind program is a novel curriculum for Israeli high school biology students, in which students are trained in the process of authentic and open scientific inquiry (Zion et al., 2004a). In the Biomind program, students observe a natural phenomenon and develop inquiry questions and hypotheses, plan and execute experiments, collect and process data, and draw conclusions. The Biomind program's open inquiry process is unique in terms of the logical thinking that is required during the development of the inquiry questions (Zion et al., 2004a, 2004b). Using several approaches, students are asked to initiate and investigate three inquiry questions logically related to each other. For example, the three inquiry questions may lead to understanding different aspects of the problem under review in parallel. In another approach, results of the first question may lead to the formulation of the second question, and results of the second question may help to formulate the third question. A combination of these approaches is also possible. For example, the first two questions are raised to examine different aspects of the same problem, and the third question may be formulated after examining some results.

In the past four years, the Biomind program operated as a pilot study in Israeli high schools. During this period, teachers raised many issues that require solutions in order to enhance and expand the Biomind program in more schools. The goal of the current research is to determine whether teachers, while performing a student-like open inquiry process, can improve their own understanding of how to implement a novel open inquiry-based curriculum into practice in schools. Figure 1 presents a model for an in-service teachers' training course designed to improve teachers' understanding of the essence of the open inquiry process and their approach to teaching an open inquiry. During the first stage of the teachers' training course, teachers conduct a student-like open inquiry process. While reflecting on difficulties that arise during their inquiry process, teachers develop new teaching strategies intended to improve the delivery of the open-inquiry process.

According to this model, we established three objectives. First, we aimed to identify difficulties that teachers experience in conducting an open inquiry. Based on success in attaining this objective, we aimed to develop together with the participating teachers strategies for coping with difficulties in performing an open-inquiry process. Our third objective was to identify how our teacher education project contributes to teachers' understanding of the essence of the open-inquiry process and their approach to teaching such a process.

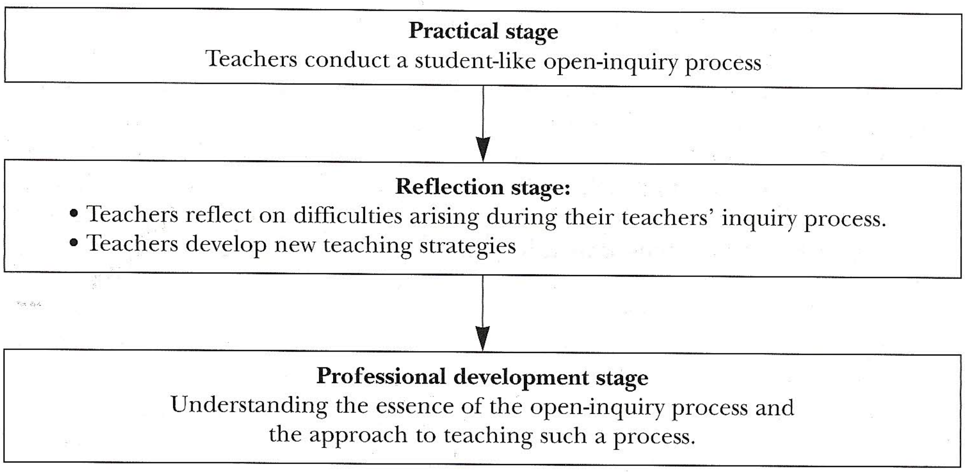

Figure 1. A model for the in-service teachers' training course for improving open inquiry teaching

Methodology

In this paper, we followed an authentic inquiry process conducted by Biomind teachers. Thirty two teachers who participated in the workshops had different teaching experience in the Biomind program. All teachers were asked to perform their own inquiry project, in which they were expected to formulate at least two related inquiry questions. Participating teachers were supported pedagogically and scientifically by science educators via telephone or electronic communication. Only few teachers were instrumental in implementing this program. These teachers are still involved in attempting to solve problems that emerged during the first years of implementation. Other teachers had one or two years of experience in the program, and for some of them this was their first experience in teaching an open inquiry.

Although 32 teachers participated in the research, only eight teachers undertook an active inquiry process. The remaining teachers were only exposed by digital communication and during face-to-face sessions to the inquiry process, which was experienced by the other eight teachers. All 32 teachers participated in face-to-face sessions held twice during the four-month project period. One session was held at the beginning of the process, focusing on the stages of identifying an interesting phenomenon and formulating inquiry questions. The second face-to-face session was held at the end of the process, focusing on identifying pedagogical solutions to problems that emerge during the open-inquiry process.

The following documents were used to analyze the results. Protocol of telephone-calls and e-mail communications between the eight teachers who performed the inquiry process and science educators and the work logs of these teachers. In addition, we analyzed the protocol of the workshop proceedings. At the end of the project, all the 32 research teachers were asked to complete an open questionnaire that examined how the workshop improved their understanding of the essence of the open-inquiry process and their approach to teaching such a process. Teachers who stated interesting points in the open questionnaire were then interviewed and encouraged to elaborate their ideas.

The analysis of the research results was performed using a qualitative approach. Arrangement and construction of information was used to interpret and understand the meaning of the data (Pidgeon, 1996). At the beginning of the analysis, data was collected from teachers' inquiry projects. We then categorized the difficulties that emerged during the teachers' inquiry process. The attributes of open inquiry (NRC, 2000, p. 29) and the characteristics of open dynamic inquiry (Zion et al., 2004b) were used as sensitizing concepts for the categorization process. Categorization focused mainly on aspects of formulating inquiry questions, a process critical to dynamic open inquiry, and on aspects of the procedural understanding of the inquiry process. Data analysis was confirmed by two researchers, in addition to the authors of this article. Data collection through triangulation of sources and the rich description of the phenomenon under review contributed to the validity of the research (Anfara, Brown, & Mangino, 2002). The reliability of the research was also checked with the teachers who performed the inquiry process.

Results

The Results section is divided into three parts according to the model in Figure 1. The first part presents the basic attributes of the inquiry process conducted by several teachers, focusing mainly on the difficulties they encountered. The second part contains suggestions that emerged during the workshop. These suggestions can assist teachers and/or students in coping with difficulties usually encountered in open inquiry. The third part presents evidence of the contribution of the teachers' training course to both teachers' understanding of the essence of the inquiry process and the essence of open-inquiry teaching.

Difficulties Arising During the Teachers' Inquiry Process.

The following is a brief account of the open-inquiry stages experienced by the eight teachers emphasizing the difficulties they encountered. Only two of them succeeded in developing their inquiry beyond the question-formulating stage.

Rachel and Ilana: Rachel and Ilana worked at the same school. Their inquiry developed as far as deciding on a topic and thinking of two inquiry questions. Although their inquiry did not go beyond describing topics and formulating inquiry questions, the discussion that proceeded to formulating of the questions was important in understanding how Biomind teachers coped with formulating inquiry questions. In the Biomind program, we recommend that students formulate one question, and then formulate the second question after observing the results of the first one. Yet, here, Rachel and Ilana were determined to have all the questions and experiments planned in advance. Ilana stated that it was important for her to conceptualize the entire picture before conducting the inquiry. The inquiry topic that Rachel and Ilana suggested was an obvious one, and the expected results can easily be found in the literature. These teachers believed that they needed to have full control over the inquiry: "*We need to see the whole picture in advance.*" They needed to avoid the vagueness and uncertainty that comes with open autonomous inquiry where one cannot predict the final results in advance.

Bilha: Bilha invested a great effort in finding an interesting inquiry topic. However, her original inquiry questions did not emphasize the different aspects of the same phenomenon. After one month, she corrected her inquiry questions and formulated them in a way indicating their interrelationship (cited in Table 1). Bilha did not continue with her project beyond developing the inquiry topic and questions.

Rita: Rita made several changes in the topic she selected. The three topics appear in Table 1. The topic was changed from a generalized topic describing the influence of automobile emissions on plant life, to a more specific and focused one, which stated the type of road and the tree species (olive). Rita raised the topics and questions while following a group of her students. Two and a half months after she started her inquiry project, Rita informed us that her students decided to change their subject and concentrate on a new topic: "*The ability of olive trees to withstand drought conditions.*" The change of topic occurred due to the need to adapt the inquiry topic to students' abilities and to conditions suitable for conducting the inquiry. The inquiry questions are cited in Table 1. Rita's questions were presented as statements, and, therefore, the authors of this article formulated them as questions. At the beginning of the inquiry process, Rita did not accept the idea that inquiry questions should be related logically to each other. Upon receiving an explanation of how questions can relate to each other, Rita then understood the difference between the statements that she formulated and the proper way to present them as questions.

Michal: While participating in the workshop, Michal prepared students for the first time for their matriculation exams in biology, and did so for the first time through the Biomind program. Michal's dual experience in teaching biology and in conducting academic biology research had an obvious effect on the way she approached her inquiry teaching. After reviewing the project goals, Michal decided to change her inquiry topic. She decided to replace a topic in which she easily mastered both the technical and theoretical points of view, due to her experience in scientific research in microbiology, to an unfamiliar topic that provided the potential to stimulate her in performing a student-like inquiry. Michal's attitude fits Kitchin's (2002) idea that providing teachers with cognitive challenges can prompt the development of 'higher teaching skills.' Although, Michal wanted a cognitive challenge, she thought that the experiment plan should be well-organized. Michal wrote: "*I tried to define for myself for the thousandth time, what I want from my Biomind students, and I (again) came to the conclusion that I want them to know how to ask interesting questions in relation to a phenomenon, and try to answer their questions by means of a well-planned experiment with the proper controls. And if this is my goal, it is impossible to go for a too complex phenomenon or too complex inquiry questions.*"

Michal's proposal was full and detailed, as indicated in Table 1. After writing her proposal, Michal stated in a Biomind teachers' discussion forum: "*During the weekend, I finally set to write the inquiry proposal for the workshop and I found it was not so easy. I began writing with confidence that the proposal will be written quickly. I ended up sitting for hours facing the computer, trying to put all my ideas into the form of an inquiry proposal.*" Michal's final inquiry proposal included four inquiry questions rather than the two as it was requested from the teachers participating in the project. Michal did not have a problem in understanding the meaning of inquiry questions that are logically related to each other. Rather, her difficulties were in a completely different area. She was challenged to find out how to adjust the existing scientific knowledge to both the student's reasoning level and the demands of the Biomind curriculum. To meet this challenge, Michal focused on finding the balance between the development of logical thinking and the students' level of reasoning.

Ruth and Racheli: In the first version of their proposal, Ruth and Racheli chose a topic that generated too many inquiry questions. Three months later, they submitted a comprehensive proposal where they listed eight different possible inquiry questions, all related to their original topic (Table 1). These teachers were asked to develop a proposal that was more limited and concentrated on several questions. Being deeply involved in the development of the Biomind curriculum, Ruth and Racheli easily proposed an appropriate set of questions. However, they seemed to have a problem in limiting their project to something appropriate for high school students. When comparing their final inquiry questions to the original ones, we realized that Ruth and Racheli were attempting to fine-tune and properly formulate their questions.

Morin: Prior to the establishment of the new Biomind curriculum, high school biology students were required to complete a practical ecological project ('Biotop'). The ecological questions raised in this type of work are significantly different from the inquiry questions found in the Biomind program: the 'Biotop' questions do not necessarily have to be logically related to one another. Teachers who moved from the previous biology practical inquiry program to the Biomind program tended to allow their students to ask inquiry questions similar to those found in the 'Biotop' program. We did not foresee such a problem occurring with new teachers who did not teach in the 'Biotop' program, or with teachers who had significant research experience. Morin is an example of a teacher who taught according the 'Biotop' program.

While participating in the workshop, Morin supervised her second class through the Biomind program. Morin was one of the two participating teachers in the workshop who actually proposed and performed an inquiry. However, her previous experience in teaching and guiding teachers in the 'Biotop' program initially prevented her to follow the instructions regarding the formulation of logically connected questions. Her first inquiry proposal (Table 1) clearly shows that she proposed a list of unrelated questions. Morin hesitated and could not decide on the most appropriate questions to investigate. From her logbook, we found that she tried to consult with other teachers, but did not obtain satisfactory help. Finally, Morin decided to concentrate on her third question and divided this question into three logically related sub-questions. These sub-questions led Morin to develop her final inquiry proposal a month after submitting her first proposal (Table 1).

Strategies Designed to Improve the Open-Inquiry Processes.

The inquiry process, followed by the eight teachers, guided the development of a workshop for the 32 participating teachers. The workshop focused on proposing solutions for the difficulties encountered by teachers during an open inquiry. The participating teachers suggested teaching strategies to overcome these difficulties which can benefit both students and teachers during the open-inquiry process (Table 2).

Table 1

Teachers' Inquiry Topics and Questions

Teacher's name	Inquiry Topics	Original inquiry questions	Final inquiry questions	Execution of the practical part of the inquiry	Characterization of the inquiry process
Rachel and Ilana	The influence of light on the development of plant seedlings; Etiolation in mung bean seedlings	1. What is the effect of light intensity on the development of mungbean seedlings? 2. What are the effects of different light wavelengths on seedling development?	none	no	* The teacher feared coping with unexpected results. * Unable to cope with the uncertainty of not knowing the outcomes of the experiments in advance. * The process terminated upon posing the inquiry questions
Bilha	The change in color with aging of the petioles of *Quisqualis indica L.*	1. What is the relationship between the period of time elapsed from the flower's opening to the flower's change of color? 2. What is the relationship between the time elapsed from flower's opening to the flower's position towards the sun? 3. Is there a relationship between the flower's change of color and the amount of nectar in the flower? 4. What is the relationship between the flower's change of color and the arrival of pollinators?	1. Unite the first two questions into one: What is the relationship between the period of time elapsed from the flower's opening, change of color and position towards the sun? 2. Is there a relationship between the flower's change of color and the flower's position towards the sun and the amount of nectar in the flowers? 3. Can we find a correlation between these four characteristics: change of color, position towards the sun, amount of nectar, and the arrival of pollinators?	no	* Final inquiry questions were related logically to each other.

Table 1 (continued)

Teacher's name	Inquiry Topics	Original inquiry questions	Final inquiry questions	Execution of the practical part of the inquiry	Characterization of the inquiry process
Rita	1. The influence of traffic roads on olive trees. 2. The influence of the noise level of an urban road (in comparison to an intercity road and a lack of roads area) on roadside olive groves. 3. The ability of olive trees to endure drought conditions.	Questions that relate to topic 4: 1. What is the effect of tree position towards the sun on morphological aspects of the tree: leaf size, average number of leaves per tree, and number of fruits per tree? 2. What is the relationship between the position of the tree towards the sun on the average level of shoots on them? 3. What is the effect of tree location on the rate of photosynthesis of olive leaves?	A new topic: The ability of olive trees to withstand drought conditions. 1. What is the effect of the irrigation level on tree morphology? 2. What is the relationship of the leaf type (olive – irrigated and non-irrigated, lemon and pine) and the transpiration rate at 40ºC? 3. What is the effect of scrubbing the cuticule and / or removing hairs on transpiration under the conditions described in question no. 2?	no	* Refinement of a very general inquiry topic to a more specific manageable topic. * The teacher adjusts her performance to the needs and abilities of her students. * The teacher had difficulties in formulating the question according to a logical thread that connects them.
Michal	1. The effect of sea water on the growth of E. coli. 2. What determines the direction of shoot and root growth of sprouts?	No questions	Questions that relate to topic 2: 1. Does the direction the seed is sown determine the success of germination? 2. Does the direction of growth of the sprout's shoot and root, which is sown "upside down" change after germination? 3. Does the humidity gradient determine the direction of root growth? 4. Does gravity determine the direction of root growth?	Michal conducted experiment s to answer the first inquiry question.	* As a teacher with experience in scientific research, Michal defined her goal as developing the scientific thinking skills of her students. While many teachers experienced problems in formulating the proper questions, this came naturally to her. * Her difficulties were actually in trying to simplify the project and adjust it to school laboratory facilities. * Michal had no difficulty in understanding how to conduct an inquiry-based project.

Table 1 (continued)

Teacher's name	Inquiry Topics	Original inquiry questions	Final inquiry questions	Execution of the practical part of the inquiry	Characterization of the inquiry process
Ruth and Racheli	1. Do red *coleus* leaves behave differently from green leaves-from both a physiological and anatomical perspective? 2. The influence of light intensity on the color changes of *coleus* leaves.	Questions that relate to topic 2: 1. Is the photosynthesis rate in red leaves different from the rate in green leaves? 2. If yes, is there a difference in chlorophyll concentration between the red and green *coleus* leaves? 3. What is the duration and pattern of change in color, when moving plants from light to shade and vice versa – checking young and mature leaf pigmentation patterns and determining if the process of color change is reversible?	1. How does moving the plant between extreme light intensities (light and shade) influence the color change of the leaves? 2. What is the relationship between the light intensity in which the plant grew and the ratio anthocyanin / chlorophyll in the leaves? 3. What is the relationship between leaf color and the rate of photosynthesis? 4. Is there a relationship between the side of the leaf exposed to illumination (red side or green side) and the photosynthesis rate?	no	Ruth and Racheli's project was characterized by two difficulties: limiting their topic to one that can be manageable by Biomind students, and fine-tuning the formulating of the inquiry questions.
Morin	1. Activity of snails 2. Effect of temperature on the activity of snails.	Questions that relate to topic 2: 1. How does soil humidity influence the activity of snails? 2. Do snails randomly disperse or do snails scatter around a specific plant species? 3. How does air temperature affect the snails' heart rate?	1. How will temperature affect the metabolism rate of snails? 2. In winter, how will the snail react to a continuous and lengthy increase in the environment temperature? 3. What is the relationship between the snail size and its heart rate at different temperatures?	Morin conducted inquiry on final questions 1 and 3.	Morin's inquiry project is an excellent example of a productive change in teacher's beliefs. Morin had vast experience in a guided inquiry curriculum, which dictated the way she formulated her original questions. Her experience in the current teacher training helped her to concentrate on a specific topic with related questions, rather than raising several topics and many unrelated questions.

Table 2
Difficulties in Performing an Open Inquiry Process and Possible Solutions

Difficulties in performing an open inquiry process	Possible solutions for learners (teacher or student) that conduct an open inquiry
Asking questions	
The question is not based on a curious and challenging phenomenon.	Small groups of learners visit nearby environment settings (yard, park, beach, forest) to search independently for intriguing phenomenon. These groups then present their phenomena in the workshop where colleagues suggest inquiry questions. During the workshops, the groups debate the characteristics of phenomena and develop appropriate inquiry questions.
There is no obvious connection between a topic and a question.	Learners indicate how the question emerged from phenomenon observed in the field, knowledge found in the literature, or a brief theoretical background of the inquiry plan.
There is no logical relationship between questions.	The inquiry plan should be approved by peers (teachers or students).
The consecutive order of questions is not always logically constructed, and the order of questions does not represent the development of the inquiry process.	Learners have to write the logical connection between the questions and the topic, and the connection between the different questions. Learners should find the relationship between the question and the topic in both field observations and in the literature.
It is difficult to change questions during the inquiry process, due to conceptual or procedural reasons. Learners tend to stick to the original inquiry plan.	Hold open inquiry workshops for teachers.
Scientific accuracy is needed	
Learners experience difficulties in defining and isolating variables. The inquiry question is not phrased precisely.	Practice in the class should improve students' ability to define and isolate variables in their own inquiry, and to formulate questions.
Learners make scientific mistakes.	Through participation in guided field observations, students can increase their scientific knowledge. The teacher provides the students with the proper background, either in class or in a laboratory, to improve the students' scientific knowledge of the inquiry topic.

Teachers' Professional Development Regarding the Teaching of Open Inquiry

Teachers' Understanding of the Essence of Open-Inquiry Process

The workshops enabled teachers to function like students in acquiring knowledge about the scientific inquiry process. The teachers specifically mentioned that the workshops enhanced their comprehension of several aspects of the inquiry process, for which they were previously unaware. "*It is so many years now that I am a teacher and not a student. It makes me forget a few things. For instance, how difficult it is to perform an inquiry project*" (Tali). The workshops served as a platform for encouraging teachers to seek solutions and overcome difficulties. Tali explained that the workshops inspired her to learn. "*Experiencing the difficulties while doing the inquiry project was refreshing, brought me a few years back, to the time I was a student in the university; it was stimulating and renewing.*"

All teachers claimed that the most significant stage that they experienced during the workshops occurred when they found a desirable phenomenon, which guided them to formulate questions. Tali explained: "*Most importantly, I learned how to notice phenomena in the field, which I find to be the most essential. While participating in the workshop sessions, I understood that it is not a 'big deal' to ask questions which are randomly related to the inquiry topic. The difficult issue is how to make those questions relevant, logically related to one another, which formulate a significant and interesting inquiry plan.*" Dvora added by saying: "*Only when I was asked to formulate by myself questions and possible hypotheses that arose from them, I realized that it is a challenge. I learned to look for a good inquiry question, and think whether the variables are included in the question. I know what can be done if the topic is very narrow.*"

The workshops also broadened teachers' views of the inquiry process overall: "*The workshop helps in the formulation of simple inquiry questions without too many variables, as well as in understanding how to identify variables that are measurable. It also helped in struggling with the analysis of results and writing conclusions*" (Orly). Tali stated that "*the workshop made clear to me the different steps which we go through during the inquiry process. I have changed my way of thinking. I understand that the final product is not important. The inquiry process itself is the most important thing: To understand how, by performing the inquiry process, we gain better understanding of the inquiry process.*" Michal commented on the contribution of the workshop to the awareness of inquiry components: "*It is amazing how much I learned about the inquiry process. More than in all the years I spent in research at the university. I used to define controls in the experiments, grasp the model of a question, which comes from observing a phenomenon and a question which follows and is built on results of a previous question. I knew these things intuitively, but teaching forced me to be aware of them.*"

To sum up, regarding the essence of the open-inquiry process, teachers generally improved their understanding of the inquiry process and particularly at the stage of formulating questions.

Open-Inquiry Pedagogical Knowledge

Teachers' experience in the inquiry process improved their pedagogical knowledge regarding the teaching of open inquiry. Orli and others stated that "*the workshops gave me an opportunity to cope with difficulties of inquiry as experienced by students.*" Michal explained: "*Taking part in the workshop helped me define what I ask the students and how I can help them. I learned, for instance, that it is better not to provide them with all of the relevant literature and avoid inhibiting their curiosity or spoon-feeding them solutions.*" Tali said: "*Today, I feel that I can better identify my students' difficulties in constructing and summarizing an inquiry project. I think I can provide them with better support along the way, because I experienced for myself the difficulties and the satisfaction in conducting the project.*"

Teachers noted an improvement in their ability to help students choose an inquiry topic and formulate inquiry questions: "*The experience in the workshop broadened my understanding in choosing realistic topics for the Biomind project*" (Michal).

"*There are good topics, which now I know how to better transfer to the students*" (Bilha). Rita understood that in order to enable significant learning during the inquiry process, she needs to assist students in formulating clear questions. The academic assistance provided in the workshops emphasized the importance of close guidance for students: "*Today it is clear to me that guiding the students through the performance of the Biomind inquiry must be very personal and close. If I, equipped with experience and knowledge (in comparison to the students), have encountered many difficulties during my inquiry process and needed advice and guidance from more experienced teachers, that surely a student will need substantial guidance. It places a heavy burden on the teacher, but this is the essence of the inquiry-learning process.*" Rita summarized by saying that "*I feel that I participated in a real experience and not just in a game. Now, I feel surer of myself, and I know that the students can trust me.*"

Discussion

Identifying and Overcoming Teachers' Difficulties in Open Inquiry

Teachers do not usually experience practical authentic inquiry either during their academic studies or in their teacher training. During this research, we encouraged in-service teachers, coping with implementing a new open inquiry curriculum, to conduct an inquiry process similar to the one required by their students. Previous research showed that pre-service teachers experience difficulties in the different stages of inquiry, including the formulation of inquiry questions (Erick & Reed, 2002). The current research indicates that inquiry training for in-service teachers is also essential. Our results show that in-service teachers improved their ability to pinpoint inquiry topics, to precisely formulate questions (Bilha, Rita, Ruth and Racheli), and to organize clusters of logically related questions (Morin). Research results show teachers' main efforts went into formulating inquiry questions. This stage required them to formulate questions regarding an intriguing phenomenon and logically relate the questions to one another. The stage in which the teacher formulated the inquiry questions also required a precise definition of variables. We realized that feedback from the project coordinator and from colleagues and teachers' own reflections can facilitate this inquiry stage.

Looking deeply into the inquiry-question formulating process, we realized that teachers had difficulties in coping with vagueness and uncertainty, which are parts of the open-inquiry process. Teachers preferred standing on safe ground in which the results were known in advance. Teachers acting according to this learning approach intended to choose a trivial topic and simple questions with results known prior to conducting the experiments. This thinking shifted the inquiry process from open to structured inquiry. In addition, teachers experienced difficulties in choosing a focused topic and formulating appropriate related inquiry questions in a way that clarified the investigated phenomenon. Teachers also tended to formulate a list of logically unrelated questions that were connected to the main topic.

We can suggest several possible explanations why only two teachers developed their inquiry beyond the question formulating stage. First, constructing a complete inquiry plan and the need to organize thoughts and ideas demand the application of advanced inquiry skills which may be unfamiliar to teachers (Zohar, 2004). In addition, building an inquiry plan is not required in many curricula and the process is therefore unfamiliar to many teachers (Chinn & Malhotra, 2002). Third, the stage in which the teacher formulated the inquiry questions occupied most of the projects' allotted time. Finally, teachers, especially those who had previous experience in teaching the Biomind program, did not think that their cooperation would enhance their professional development and they were reluctant to spend their time on conducting the full inquiry to its completion.

Several teachers were among the supervisors of the Biomind program (Dvora, Ruth, and Racheli) and were continuously exposed to discussions about program difficulties. These teachers had difficulty in implementing their inquiry project to practice. Perhaps their vast exposure to problems in the Biomind curriculum hindered their ability to think of new original ways to overcome similar difficulties by themselves. In addition, we found that the teachers who participated in the research (all had pedagogical experience in in-service teaching) applied pedagogical aspects in their practical inquiry activity. Teachers also improved their inquiry questions by searching for simple questions suitable for study and experimentation in the school environment. Teachers who had advanced academic experience paid special attention to this aspect (Michal, Ruth, and Racheli).

Implications and further research

Teachers reported that they overall experienced enhanced understanding of the essence of the inquiry process and especially in the question-formulation stage. Deeper understanding of the nature of the scientific inquiry helped teachers clarify pedagogical aspects of inquiry teaching. Moreover, conducting a full and open inquiry process encouraged teachers to explore suggestions that may help both teachers and students in their attempts towards performing an open inquiry. Suggestions focused on establishing students' scientific knowledge, on the importance of carefully formulating questions and planning inquiry plans, and on the significance of providing teacher support through the process of teaching.

We propose that teachers should be trained in an open-inquiry process during the first stage of their pre-service teacher training and receive additional training in continuing education courses as they progress in their career. This research shows that the second stage of preparing in-service teachers for the teaching of open inquiry is important, because a combination of experience in teaching and conducting science appears to support the critical aspects of an inquiry-oriented science teacher education program, as suggested by Erick and Reed (2002).

Acknowledgements

We wish to thank Bruria Agrest, Ruth Mendelovici, Rachel Nussinovitch, Talmona Orian and Ilana Adar for their fruitful cooperation. We would like to thank Ori Stav, and Yosef Mackler for their editorial assistance. This research was supported by the Israeli Ministry of Education, and Schnitzer Foundation for Research on the Israeli Economy and Society.

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