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Inquiry practices and types of knowledge, with paths of logical associations between inquiry questions, presented as part of an open inquiry process

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ABSTRACT

We examined inquiry practices and types of knowledge presented along with paths of logical associations between inquiry questions as part of an open inquiry process.

The study analysed high school biology students' scientific summaries of open inquiry processes. We found three paths of logical associations between inquiry questions – preliminary to major, major to major and major to theoretical. Planning and design inquiry practices were implemented at similar rates in all paths. Analysis and interpretation practices were highest in the preliminary to major path and application inquiry practices were highest in the major to major path. In the preliminary to major path, procedural, logical, and strategic knowledge was used. Logical and situational knowledge were used in the major to major path, and situational knowledge was used in the major to theoretical path. Our results demonstrated that various inquiry practices and types of knowledge are used at different paths of formulating inquiry questions, specifically those that involve several stages of hands-on activity. Thus, we recommend that high school students should engage in different paths of scientific inquiry processes, specifically those that require them to engage in continuous planning and performing hands-on inquiry activity, to advance inquiry practices and their knowledge base.

KEYWORDS

Logical thinking; open inquiry; practices; types of knowledge

Introduction

Many international educational bodies emphasize the importance of scientific inquiry practices (e.g. European Commission 2015; National Research Council , 2012a, 2012b). Open inquiry is the most complex level of inquiry-based learning, requiring students to formulate the inquiry questions, select the inquiry approach, and be involved in decision-making at every stage of inquiry-based learning (Zion and Mendelovici 2012).

Students who perform open inquiry are faced with cognitive challenges. They acquire and apply different practices during the learning process, such as asking a question, planning and performing experiments, and learning from mistakes. Students are engaged in continuous decision-making throughout the inquiry process. To perform open inquiry, students also must apply several types of knowledge, such as situational, conceptual, procedural, strategic, and logical knowledge. Students ask inquiry questions concerning intriguing biological phenomena of their choice. To find comprehensive answers, the inquiry questions should be logically associated (Zion and Sadeh 2007).

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The notion of a logical association between inquiry questions as the core structure around which the open inquiry plan is constructed emphasizes the importance of questioning and logical thinking within this challenging learning setting (Zion, Cohen, and Amir 2007). This paper presents a study that focuses on analysing the process of logical thinking in the various stages of the open inquiry-based learning process.

This study focuses on the challenging learning process of open inquiry and its required cognitive components – a path of logical associations between inquiry questions, practices, and types of knowledge. The novelty of this study is its examination of the relations between these components in an open inquiry process.

The study analyses the types of knowledge and practices students acquire during the learning process. This study aimed to find differences in the inquiry practices and the types of knowledge demonstrated by groups of high school biology students for different paths of logical associations between inquiry questions in open inquiry projects.

Theoretical background

The study's theoretical background presents the components that are its focus: inquiry practices, types of knowledge, and paths of logical associations between inquiry questions. The relations between these components are organized into the research goals and questions at the end of this section.

Scientific inquiry and open inquiry

Inquiry is a major worldwide approach in science, technology, engineering, and mathematics (STEM) education (Sergis et al. 2019). The National Research Council (NRC) science framework, for example, emphasized the importance of sufficient knowledge of science and engineering for students to engage in scientific discussion and be careful consumers of technology in their everyday lives (National Research Council , 2012a). Scientific inquiry is an investigative activity employed systematically by scientists to explain phenomena of the natural world (National Research Council 2000). Building scientific knowledge requires asking and answering questions by gathering and interpreting data (Duschl 2020), as is done in inquiry-based learning. Thus, in science education, inquiry is a method for students to learn both scientific knowledge and practices; many international educational bodies emphasize its importance in science education (e.g. European Commission 2015; National Research Council , 2012a; Organization for Economic Co-operation and Development 2016; NGSS Lead States 2013). The Next Generation Science Standards (NGSS Lead States 2013) fully integrate scientific knowledge and practices (Furtak and Penuel 2019). There are several reasons for promoting autonomous inquiry in science education. Among these reasons is the notion of 'students as scientists'. In following this notion, students investigate phenomena in which they are interested and enjoy the opportunity for actual scientific research, thus increasing the authenticity and the motivation to carry on to further studies of science (Bennett et al. 2018; Burgin 2020).

The Framework for K-12 Science Education (National Research Council , 2012a) and the NGSS (NGSS Lead States 2013) both emphasize that students should examine evidence in long-term investigations. This evidence examination is realized in scientific inquiry, an instructional strategy characterized by being student-centred, thereby providing opportunities for students to plan and conduct a scientific investigation of their own (Singer et al. 2000). Inquiry-based learning includes a broad spectrum of students' autonomy, ranging from teacher-directed guided inquiry to student-directed open inquiry (National Research Council 2000).

Open inquiry is the most complex level of inquiry, as in this method, students are responsible for planning and performing the entire inquiry process (Zion and Mendelovici 2012). In open inquiry, the students plan and conduct the full inquiry process, starting with finding the phenomenon to be investigated, continuing through formulating the inquiry questions and selecting the methods for investigation, and ending with reaching conclusions from the entire inquiry process (Sadeh and Zion 2012; Zion and Mendelovici 2012). Furthermore, because the open inquiry is not linear and requires decision-making at different stages along the inquiry process, it is a complex process with high uncertainty (Baur and Emden 2021). Thus, open inquiry simulates most closely the research and type of work performed by scientists (Banchi and Bell 2008; Zion, Cohen, and Amir 2007). Open inquiry is based on open-ended investigations in which there are no correct answers; different paths can lead to any number of solutions. In such an inquiry, the students examine and change the practices based on the data gathered throughout the inquiry process (Roberts, Gott, and Glaesser 2010).

Various studies demonstrated the learning gains of open inquiry. Engaging in open inquiry helps students learn science content and skills and develop scientific thought, a passion for investigation, and an interest in science (Kapon 2016). This is especially true when teachers help the students make sense of their experiments, which was shown to increase the learning gains (Aditomo and Klieme 2020). During open inquiry, the students employ inquiry skills, engage in high order thinking (Krystyniak and Heikkinen 2007; Zohar and Resnick 2021), and develop creative thinking such as flexibility and originality (Kadir and Satriawati 2017). Furthermore, critical thinking, which is at the core of science and a 21st-century essential skill, is also central in science education. Critical thinking can be developed through answering scientific questions (Osborne 2014). Grasping evidence and criticizing it requires analysis, evaluation, interpretation, and integration (Golan, Chinn, and Barzilai 2018). The Framework for K-12 Science Education and other current studies all emphasize that answering scientific questions requires engaging in the processes of observation and data collection (National Research Council , 2012a; Tawfik et al. 2020). Processes such as these are inherent in scientific inquiry, especially so in open inquiry.

Inquiry practices

The NGSS (NGSS Lead States 2013) uses 'scientific practices', emphasizing that knowledge and skills should be combined to enhance scientific literacy. Other programs worldwide (Australian Curriculum, Assessment and Reporting Authority 2012; Department for Education 2014), as well as research in science education (e.g. Lederman et al. 2014; Roberts and Johnson 2015), also emphasize the thinking and understanding behind the process of scientific inquiry, which is entailed in the current conception of inquiry practices. The NGSS view of science as a set of practices relates to the notion that scientists engage in specialized activities, such as reasoning and scientific writing (Lehrer and Leona 2006). These practices are at the core of scientific investigation, which is focused on developing evidence-based explanations of the natural world (Manz, Lehrer, and Schauble 2020; Windschitl, Thompson, and Braaten 2008). Similarly, to develop scientific knowledge, students should use scientific practices in a meaningful way (Berland et al. 2016). Reforms and investigators have emphasized over the years that hands-on activities are not enough to develop scientific knowledge and understanding (Furtak and Penuel 2019). For example, Abrahams and Reiss (2012) suggested that hands-on and minds-on approaches should be linked to develop conceptual understanding. It was also shown that open inquiry promotes conceptual understanding (Engudar, Sarioäÿlan, and Dolu 2020). Scientific inquiry can include a wide range of activities, yet the base for every inquiry involves hands-on activities combined with cognitive activities. Lunetta and Tamir (1979) stated that hands-on activities in science education should be based on goals in terms of inquiry skills. To help define these goals and better represent the phases of inquiry, they divided the basic skills and behaviours related to scientific inquiry into four categories:

a. 'Planning and design' - skills required at the first stage of the inquiry and include formulating questions and hypotheses, predicting results, and designing the procedures for investigation.

b. 'Performance' – the stage of the inquiry in which the students perform the hands-on activity. At this stage, the students use skills such as making decisions about the investigation techniques, observations, and data collection.

c. 'Analysis and interpretation' – at this stage, the students process, analyse, explain and discuss the data, arrive at generalizations, point at assumptions and limitations, and formulate questions for further investigation.

d. 'Application' – this category includes skills beyond the particular investigation, such as making predictions for different situations, formulating hypotheses based on the results, and using the inquiry techniques for other problems.

Types of knowledge

The PISA 2015 definition of science literacy includes contexts, knowledge, competencies, and attitudes. Of these, knowledge is defined as: '[a]n understanding of the major facts, concepts, and explanatory theories that form the basis of scientific knowledge. Such knowledge includes knowledge of both the natural world and technological artifacts (content knowledge), knowledge of how such ideas are produced (procedural knowledge), and an understanding of the underlying rationale for these procedures and the justification for their use (epistemic knowledge)' (Organization for Economic Co-operation and Development 2016, 25)

A personal knowledge base is composed of different types of knowledge. The PISA taxonomy (e.g. Aydın and Özgeldi 2019) stands with that of de Jong and Ferguson-Hessler (1996).

There are several approaches for developing a systematic description of knowledge. These approaches are based on cognitive theories, epistemological points of view, or approaches built, upon which to base instructional design theories (de Jong and Ferguson-Hessler 1996). Thus, there are multiple different taxonomies for types of knowledge used for different purposes. For example, Carson (2004) proposed a taxonomy to assist educators in designing curricula.

Using this taxonomy can help distinguish between types of knowledge, giving educators the opportunity to choose different strategies to develop different types of knowledge. With regard to scientific inquiry, the new framework for K-12 science education in the US (National Research Council , 2012a) states that scientific inquiry requires both practice and knowledge: 'Science is not just a body of knowledge that reflects current understanding of the world; it is also a set of practices used to establish, extend, and refine that knowledge. Both elements – knowledge and practice – are essential' (p.26). The PISA 2015 terminology for scientific knowledge refers to three elements: content knowledge (knowledge about science – facts, concepts, and theories), procedural knowledge (knowledge of procedures used to gain scientific knowledge), and epistemic knowledge (understanding of the role of constructs and features required for building knowledge) (Organization for Economic Co-operation and Development 2016). The knowledge employed during the process of scientific inquiry can be represented as knowledge-in-use (de Jong and Ferguson-Hessler 1996), meaning that the knowledge base is characterized by its function in performing a specific task. Thus, the task identifies the types of knowledge, specifically those that enable performing the task (Aydın and Özgeldi 2019). This classification can serve to characterize the types of knowledge employed in scientific inquiry. de Jon and Ferguson-Hessler (1996) divide the knowledge base into four types of knowledge:

a. 'Situational knowledge' – knowledge about typical situations in a specific domain. Situational knowledge facilitates the ability to extract relevant information that enables the representation of the problem so that additional types of knowledge may arise.

b. ‘Conceptual knowledge’ - knowledge of facts, concepts, and principles of a specific domain. Adds information used to solve a problem.

c. ‘Procedural knowledge’ – actions and procedures associated with a domain. Procedural knowledge enables the transfer from one problem to another.

d. ‘Strategic knowledge’ - enables organizing a process for problem-solving – a plan for a sequence of action to reach a solution.

The process of open inquiry requires a high degree of association between the different inquiry stages. Thus, we consider another type of knowledge employed in scientific inquiry, ‘logical knowledge’, a mental model of sequenced connections, which is, 'what leads to what' – the essence of causality. Logical reasoning emphasizes selecting and interpreting information from a given context, making connections, and verifying and drawing conclusions based on provided and interpreted information and the associated rules and processes (Bronkhorst et al. 2020). According to self-regulated structures, logical knowledge enables interpreting a task and planning its solutions through logical reasoning (Cauley 1986). Logical knowledge is employed in scientific inquiry.

Knowledge classification can enable the examination of students’ knowledge during an open scientific inquiry, as performing the inquiry requires students to know scientific facts and procedures (Roberts 2001). Thus, during the learning process, the students must gain and improve both knowledge of the contents of the subject matter and procedural knowledge (Carson 2004; McDonnell and Mullally 2016). During the inquiry process, logical knowledge and conceptual knowledge also develops, as the learning process entails knowledge integration into higher levels of complexity (Schönborn and Susanne 2009).

Paths of logical associations between inquiry questions

Critical thinking includes a logical process of reflection and development, which can be defined as an inquisitive attitude coupled with the logical application of skills in problem-solving contexts (Niu, Behar-Horenstein, and Garvan 2013). The importance of critical thinking becomes ingrained as an important outcome of the process of how students learn. Using open-ended, authentic problem contexts can foster critical thinking in students. (Lai 2011). Formulating several inquiry questions throughout an open inquiry process requires students to think of the logic that links the questions. Logical thinking in an open inquiry process may take place at different stages of the process: when conducting the preliminary experiments that lead to the construction of the main inquiry setting; while raising a continuous inquiry question after receiving the results of the first question; and while considering whether the results reject, or fail to reject, the hypothesis. Zion and Sadeh (2007) introduced logical-based scenarios for establishing logical associations between inquiry questions in an open inquiry process that includes several inquiry questions. Scenarios such as this can serve as a framework for facilitating scientific thinking during the open inquiry learning process. Specifically, the open inquiry learning process, which is based on several inquiry questions, requires the students to understand and explain the connection between the inquiry questions (i.e. their logical associations).

The high school biology program used in Israel includes an open inquiry learning process called the bio-inquiry program (Israel Ministry of Education 2014). The instructions for the bio-inquiry program state that the inquiry project must include at least one major inquiry question, one that is based on existing biological knowledge and is related to the biological phenomena being examined. The logical associations between inquiry questions can be of three paths (Figure 1):

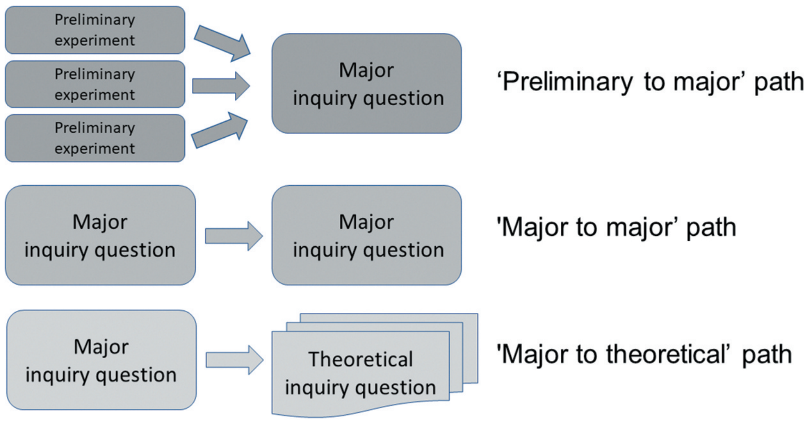

Figure 1. The paths of logical associations between inquiry questions.

a. In the 'preliminary to major' path, students first formulate and examine preliminary experiments, the results and conclusions of which lead to formulating and examining a major inquiry question.

b. The 'major to major' path includes two major inquiry questions. In this path, the conclusion of the first inquiry question is the basis for formulating and examining an additional inquiry question.

c. The 'major to theoretical' path includes formulating and examining a major inquiry question followed by formulating a theoretical inquiry question. In this path, the first inquiry question requires long-term experiments. The conclusion of the first question leads to formulating a second inquiry question. This second question remains theoretical, as the scope of the inquiry does not allow sufficient time for it to be examined.

This study examines the paths of logical associations between inquiry questions in an open inquiry process, focusing on how the inquiry practices and types of knowledge differ by these paths of logical associations between inquiry questions.

Key objective and research questions

Scientific inquiry provides students with an opportunity to learn science content and skills, especially regarding open inquiry (Sadeh and Zion 2012). Conducting an open inquiry learning process requires high-order thinking involving a varied knowledge base (Ben-David and Zohar 2009). Furthermore, logical thinking is critical for constructing an inquiry process based on a logical association between inquiry questions (Zion and Sadeh 2007).

Roberts (2001) and Sadeh and Zion (2012) demonstrated that various knowledge and inquiry practices develop through engaging in scientific inquiry. Open inquiry enables students to develop their own inquiry process, leading them to different paths of logical associations between inquiry questions (Zion and Sadeh 2007). Considering this, the goal of this study was to examine the different paths of logical associations between inquiry questions in open inquiry processes that were performed by groups of high school biology students; this, along with inquiry practices, and the quality of types of knowledge demonstrated by the groups of students.

The research questions for this study were:

1. What are the paths of logical associations between inquiry questions in the open inquiry processes, and what are their frequencies?

2. How do the inquiry practices demonstrated by the students differ by the paths of logical associations between the inquiry questions?

3. How does the quality of various types of knowledge demonstrated by the students differ by the paths of logical associations between the inquiry questions?

We previously showed that performing an inquiry process in response to an inquiry question led to formulating successive inquiry questions that involved high levels of uncertainty and required the students to exercise high-level cognitive efforts (Zion and Sadeh 2007). We thus expect that, compared with other paths, the paths of logical associations between inquiry questions that include several successive hands-on stages will be connected to more inquiry practices and more types of knowledge.

Methods

The research context: the open inquiry processes

The instructions for the open inquiry process that is the basis for this study (Israel Ministry of Education 2014) lead to inquiry projects that include several inquiry questions. The Israel high school biology program requires students to engage in an open inquiry project, in addition to their theoretical studies. The current Israel high school biology curriculum comprises the bio-inquiry program, in which students are engaged in an open inquiry learning process. The bio-inquiry program was implemented at several schools starting in 2009; beginning in 2014, all high school biology students must participate in the bio-inquiry program. The program's value can be seen by the fact that student performance in the bio-inquiry project composes 30% of the final biology matriculation exam grade. During the inquiry project, students are required to formulate their own inquiry questions, select the inquiry approach, and be involved in decision-making at every step of the way. As the bio-inquiry project is open-ended, the students face uncertainty about the design of the experiments, the evidence, and their interpretation. The bio-inquiry instructions (Israel Ministry of Education 2014) state that the students should conduct an original inquiry project. They can base their investigation on existing protocols, but in such cases, the students must adapt the study design to answer their own inquiry questions. This adaptation, often called 'fingerprinting', can occur at different points during the project, such as changing the type of measurements, adding more treatments or controls, or changing the range of measurements.

All bio-inquiry projects must include at least one major inquiry question based on existing biological knowledge and related to the examined biological phenomena. The inquiry project is constructed in one of three paths of logical associations between inquiry questions (Israel Ministry of Education 2014; Figure 1).

As in other open inquiry processes, uncertainty components are inherent in all three paths of logical associations between inquiry questions in the bio-inquiry program. In the preliminary to major path, the students design and set up a unique experimental system to examine their inquiry question. As such, the inquiry results are unknown – to the students and their teacher. At the end of the inquiry project, student reports include the results of the preliminary experiments leading to the major question about the experimental system and the results of the major inquiry question examined. In the major to major path, the students ask and examine the first inquiry question. The results of the first part of the inquiry, which are unknown at the beginning of the inquiry, lead to formulating and examining a second inquiry question. In the major to theoretical path, the students perform a long-term experiment, the results of which are unknown. Based on the results of the long-term experiment, the students formulate a second inquiry question, which is not examined in the scope of the inquiry project. This option is employed when the inquiry design includes long-term experiments and students do not have time to perform another experiment during the time permitted for the inquiry project. In all paths, the students must explain the logical association between the inquiry questions presented in their project. Upon completion, the students are required to present their open inquiry project in a scientific summary.

Research population

To collect data for the study, we approached thirty experienced high school biology teachers who participated in professional development workshops supporting the adaptation of the bio-inquiry program into the biology high school curriculum. These teachers implemented the bio-inquiry program with their students throughout the years 2011–2015. Twenty-one of these teachers agreed to participate in the study and share their students' scientific inquiry summaries with us. Following the teachers' agreement, we examined the scientific summaries written by their students: 285 biology students (40% boys and 60% girls) from the 11th and 12th grades of 16 different high schools. All students had chosen biology as their major and took the final biology matriculation exams. The students worked either singly or in groups of two or three students: 40% of the groups included three students, 51% included two students and 9% included one student. In total, all groups of students participating in this study produced a total of 116 scientific inquiry summaries. The summaries identified the students' projects and referred to inquiry questions. In the summaries, the students documented the phenomena examined, referred to the biological basis, hypotheses, and described the findings of their inquiry projects. We noted 176 logical associations between inquiry questions within these summaries, which were the basis for examination.

Research tools

The study combined quantitative and qualitative research, enabling rich data collection and analysis (Burke, Onwuegbuzie, and Turner 2007). The basic unit of analysis was the logical association between each pair of inquiry questions presented in the students' scientific summaries of their inquiry projects. The logical associations between inquiry questions, the inquiry practices, and the types of knowledge presented in the summaries were examined by two researchers. The researchers are also experienced high school biology teachers. As the open inquiry processes were mostly performed and reported by groups of students, the analysis represented practices and knowledge presented by the groups. For validity purposes, the researchers worked separately on analysing the data. The researchers agreed with regard to their separate analyses of 91% of the data. They then worked together and ultimately reached agreement on the remaining 9% of the data. The values written for each association between inquiry questions, practice, and type of knowledge were agreed upon by the researchers. For each unit of analysis, the inquiry practices and the types of knowledge applied were determined separately; thus, the units of analysis were independent of each other.

Assessment of inquiry practices

Each pair of inquiry questions presented in the students' scientific summaries was examined to determine the inquiry practices used, enabling the logical association between these inquiry questions. The inquiry practices were analysed using the following procedure.

First the inquiry practices were characterized and divided into three categories, after Lunetta and Tamir (1979): planning and design, analysis and interpretation, and application. The performance practices, representing hands-on activities, were not examined in this study. Even the hands-on open-inquiry process itself was excluded from examination. Only the student-written scientific summaries were examined. Second within each logical association between inquiry questions, the inquiry practices of each category were scored at one of the following levels: not mentioned or not clear (1), mentioned but not well explained (2), mentioned and well explained (3). Appendix 1 (1a, 1b) provides details and examples. Third, the scores for each category of inquiry practices in each logical association between inquiry questions were summed, with scores for each category of inquiry practices in the examined path of logical associations. Because the sum for each category of inquiry practices was different, the means and standard deviations for each category were converted to a scale of 1–100. Fourth, the scores for all 176 logical associations between inquiry questions for each category of inquiry practices were averaged, creating a value for that category within each path of logical associations.

The classification was performed separately by two judges who were senior biology teachers and investigators. This procedure was followed to reduce the influence of bias. The judges agreed in 91% of the cases. As to those cases with no initial agreement, the judges discussed the case until an agreement was reached.

Assessment of types of knowledge

Each pair of inquiry questions presented in the students' scientific summaries was also examined for the types and quality of knowledge that led to the logical association between each inquiry question pair. The analyses of the types and quality of knowledge were done using the following procedure: First the knowledge presented within each logical association between inquiry questions was characterized and divided into one of five types of knowledge: procedural, conceptual, logical, situational, and strategic (de Jong and Ferguson-Hessler 1996; Farnham-Diggory 1994). Second, quality of knowledge was determined loosely after de Jong and Ferguson-Hessler (1996): Level of knowledge was graded as surface (1) or deep (2); structure of knowledge was graded as isolated elements (1), loosely connected (2), or structured knowledge (3). The quality of knowledge for problem-solving was graded as general steps for defining the problem components (1) or specific steps (2). Appendix 2 (2a, 2b) provides details and examples. Third the scores for each type of knowledge in each association between inquiry questions were summed, scoring for each type of knowledge in the examined path of logical association. Because the sum for each knowledge type was different, each type's means and standard deviations were converted to a scale of 1–100. Fourth the scores for all 176 logical associations between inquiry questions for each type of knowledge were averaged, creating a value for that type of knowledge within each path of logical associations.

As was done with the practices, classification of knowledge types and levels were also carried out separately by the two judges, following the same procedure used to reach an agreement.

Data analysis

Data were analysed with SPSS version 25. The unit of analysis in this study was the logical association between inquiry questions within open inquiry students' projects. There were 176 such logical associations in 116 projects. About 50% of the projects (n = 57) had one logical association, and most others had two such logical associations between inquiry questions. As the focus of this study, the unit of analysis was the logical association (n = 176) of all variables (inquiry practices and quality of types of knowledge) that were defined within a logical association. In other words, all variables were unique to each logical association within an inquiry project, and there were no variables at the second level of the inquiry project. Thus, the analytic strategy included frequencies and percentages for RQ1 and multivariate analyses of variance (MANOVAs) for RQ2 and RQ3 (rather than multilevel modelling).

Results

Paths of logical associations between inquiry questions

According to the first research question, we examined the paths of logical associations between the inquiry questions within the open inquiry projects. We found that most logical associations arose from examining preliminary results to formulating and examining a major inquiry question

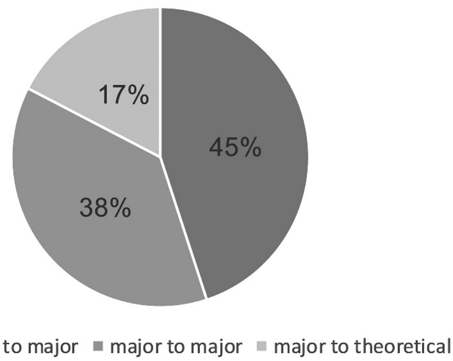

Figure 2. Percentage of paths of logical associations between inquiry questions (n = 176).

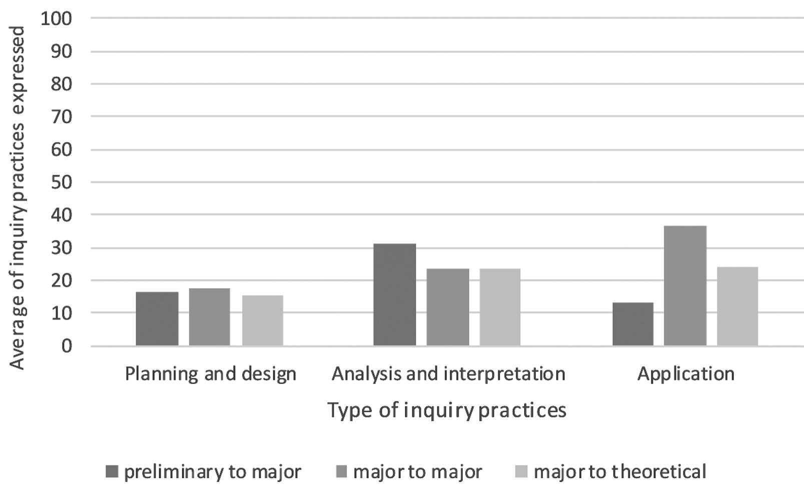

Figure 3. Inquiry practices expressed at the different paths of logical associations between inquiry questions.

(preliminary to major – 45%), and from examining a major inquiry question to formulating and examining a second inquiry question (major to major – 38%). Fewer logical associations arose from examining a major inquiry question to formulating a theoretical inquiry question (major to theoretical – 17%) (The unit of analysis: n = 176 logical associations) (Figure 2).

To examine whether there is a significant difference between the frequencies of the three paths of logical associations, we performed a Chi Square (χ^2) test with significant results ($\chi^2(2) = 36.25$, $p < .001$). Paired Z tests revealed no significant difference in the frequency of preliminary to major and major to major paths ($Z = 1.78$, $p = .075$). There was, however, a difference between the paths of preliminary to major and major to theoretical ($Z = 9.76$, $p < .001$), and between major to major and major to theoretical ($Z = 7.36$, $p < .001$) (The unit of analysis: a logical association). Thus, logical associations of examining preliminary results to formulating and examining a major inquiry question, and logical associations of examining a major inquiry question to formulating and examining a second inquiry question, were expressed at similar rates, higher than that of examining a major inquiry question to formulating a theoretical inquiry question.

Table 1. Means and SDs of inquiry practices expressed at the different paths of logical associations between inquiry questions.

	Planning and design			Analysis and interpretation			Application		
	N	M	SD	N	M	SD	N	M	SD
Preliminary to major	79	16.34	8.27	79	**31.13	13.26	79	13.13	20.66
Major to major	67	17.38	6.20	67	23.40	13.77	67	***36.57	28.98
Major to theoretical	30	15.39	7.10	30	23.44	14.40	30	24.19	24.57

**$p < .01$, ***$p < .001$

Inquiry practices presented in the paths of logical associations between inquiry questions

To examine the second research question concerning the inquiry practices as presented in the different paths of logical association between inquiry questions, we classified the inquiry practices demonstrated in the students' scientific summaries into planning and design, analysis and interpretation, and application categories. These practices were divided into sub-practices in each logical association between inquiry questions. The scores for each category of inquiry practices within each logical association between inquiry questions were summed, making a total score for that category in the examined association between inquiry questions. The average for all 176 logical associations (the unit of analysis is the logical association) between inquiry questions for each category of inquiry practices is presented in Figure 3.

A MANOVA was used to assess the extent of inquiry practices by the logical associations between inquiry questions. It revealed a significant difference in the categories of inquiry practices by the three paths of logical associations between inquiry questions (F (6, 344) = 12.58, $p < .001$, $\eta2 = .180$). A significant difference was found for the inquiry practices analysis and interpretation (F (2,175) =7.03, $p < .01$, $\eta^2 = .074$) and for application (F (2,175) =16.35, $p < .001$, $\eta^2 = .157$). No difference was found for planning and design. Post-hoc Tukey analyses showed that on average, analysis and interpretation inquiry practices were significantly higher in the preliminary to major path of logical associations (31.13) than in both the major to major path (23.4) and the major to theoretical path (23.44). Application inquiry practices were significantly higher in the major to major path (36.57) than in the preliminary to major (13.13) and major to theoretical (24.19) paths of

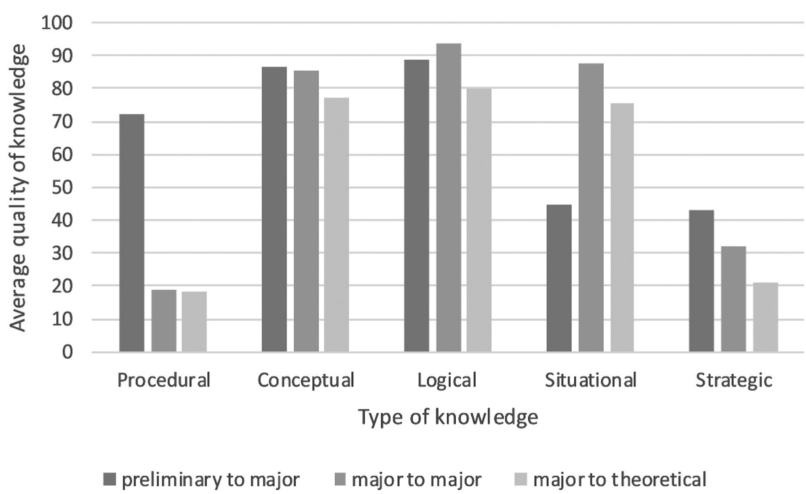

Figure 4. Types and quality of knowledge expressed at the different paths of logical associations between inquiry questions.

Table 2. Means and SDs of types and quality of knowledge expressed at the different paths of logical associations between inquiry questions.

	Procedural Knowledge			Conceptual knowledge			Logical knowledge			Situational Knowledge			Strategic Knowledge		
	N	M	SD	N	M	SD	N	M	SD	N	M	SD	N	M	SD
Preliminary to major	79	72.15***	38.94	79	86.67	23.23	79	89.03	15.81	79	44.93***	42.33	79	42.99*	42.51
Major to major	67	18.91	35.12	67	85.66	23.73	67	93.95	13.6	67	87.48	21.85	67	32.34	43.12
Major to theoretical	30	18.10	35.34	30	77.24	26.35	30	79.93***	19.76	30	75.81	19.33	30	21.33	34.70

*p < .05, **p < .01, ***p < .001

logical associations (See Figure 3) (The unit of analysis is the logical association, n = 176). Table 1 presents the means and standard deviations for the three categories of inquiry practices by the different paths of logical associations between inquiry questions.

Types and quality of knowledge presented in the paths of logical associations between inquiry questions

To examine the third research question, concerning the quality of the various types of knowledge by the three paths of logical association between inquiry questions, we classified the knowledge demonstrated in the students' scientific summaries into five categories: procedural, conceptual, logical, situational, and strategic. The quality of knowledge was evaluated as well. The scores for each type of knowledge within each association between inquiry questions were summed, creating a total score for that type of knowledge in the examined logical association between inquiry questions. The average for all 176 logical associations between inquiry questions for each type of knowledge is presented in Figure 4 (The unit of analysis is the logical association, n = 176).

A MANOVA was used to assess the quality of various types of knowledge by the logical associations between inquiry questions. It revealed a significant difference in the quality of types of knowledge presented at the three paths of logical associations between inquiry questions (F (10, 340) = 16.84, p < .001, η2 = .331). A statistically significant difference was found within four of the five types of knowledge: procedural knowledge (F (2,175) =46.23, p < .001, η^2 = .346), logical knowledge (F (2,175) =8.37, p < .001, η^2 = .087), situational knowledge (F (2,175) =32.95, p < .001, η^2 = .274), and strategic knowledge (F (2,175) =3.30, p < .05, η^2 = .036). No difference was found for conceptual knowledge. Post-hoc Tukey analyses showed that on average, the quality of procedural knowledge was significantly higher in the preliminary to major path (72.15) than in both the major to major (18.91) and the major to theoretical (18.10) paths of logical associations between inquiry questions. The Post-hoc Tukey analyses also showed that on average, the quality of logical knowledge was significantly higher in the preliminary to major path (89.03) and in the major to major path of logical associations between inquiry questions (93.95) than in the major to theoretical path (79.93). The quality of situational knowledge was significantly higher in the major to major path (87.48) and the major to theoretical path (75.81) than in the preliminary to major path of logical associations between inquiry questions (44.93). The strategic knowledge quality was significantly higher in the preliminary to major path (42.99) than the major to theoretical path (21.33). The average quality of strategic knowledge in the major to major path of logical associations between inquiry questions (32.34) was not statistically different than in both other paths (See Figure 4). Table 2 presents the means and standard deviations for the quality of types of knowledge by the different paths of logical associations between inquiry questions.

Discussion

In this study we examined inquiry practices (Lunetta and Tamir 1979) and types of knowledge (de Jong and Ferguson-Hessler 1996; Farnham-Diggory 1994) presented in different paths of logical associations between inquiry questions in an open inquiry process. The data for analysis was gathered from scientific summaries written by biology students in the 11^{th} and 12^{th} grades after participating in open inquiry projects. These summaries present the inquiry process performed by the students, who worked mostly in groups. Thus, analysing the summaries let us detect the inquiry paths chosen by the students' groups and the frequencies of the practices and types of knowledge they used. These practices and knowledge are required for performing open inquiry processes.

Paths of logical associations between inquiry questions in bio-inquiry open inquiry projects

The bio-inquiry project allows the students to plan their inquiry process. Pedaste et al. (2015) introduced a framework describing the different phases of the inquiry cycle. The framework refers to different pathways that can be employed during the inquiry process. Diversification in the inquiry process, such as this, is demonstrated in the students' bio-inquiry scientific summaries examined in the current study; within those summaries, we found three paths of logical associations between inquiry questions. The students employed these paths of logical associations at different stages of the inquiry process and different starting points within the inquiry cycle. Two paths of logical associations between inquiry questions, the preliminary to major and the major to major, were expressed at similar rates; both were higher than the third, major to theoretical, path.

The bio-inquiry instructions state that students engaged in answering an inquiry question by a long-term inquiry process can then formulate a theoretical inquiry question rather than performing another hands-on experiment (Israel Ministry of Education 2014). Our results show that significantly fewer students chose this path rather than the other two paths. This choice might be surprising, as students may view this path as less demanding. It should be noted that the first stage of the major to theoretical path is long and does not allow for setting preliminary experiments. Thus, the teachers often present the students performing such inquiry with the instructions for gathering information during the inquiry process. Presenting these instructions somewhat resembles a guided inquiry process (Sadeh and Zion 2012). Choosing the major to theoretical path might reflect the characteristics of the students choosing it. Zion and Sadeh (2007) showed that less curious students choose inquiry paths with a predetermined framework. Of the three bio-inquiry paths, the major to theoretical path provides the students with the most certainty. However, in this path, the students can still face possible setbacks that might compromise the experimental system, such as the death of the model organism. While this path might not be as intriguing as the other paths, it requires other student characteristics, such as determination and perseverance, because experiencing the major to theoretical inquiry path requires a long-term inquiry process. Not choosing the major to theoretical path may reflect the teachers' and students' commitment to the full open inquiry process performed in the other two paths.

Many of the logical associations between inquiry questions are of the preliminary to major path, where students perform a set of experiments to determine the conditions under which the major question is then examined. Students performing such inquiries are faced with high degrees of uncertainty and dynamic inquiry. Curious students tend to choose an inquiry process of this nature (Zion and Sadeh 2007). Students working in groups of three must answer two major inquiry questions (Israel Ministry of Education 2014). The bio-inquiry instructions (Israel Ministry of Education 2014) stipulate that the students must set the conditions for examining the major inquiry question by performing preliminary experiments or basing the examination on the existing literature. Thus, choosing the major to major logical association between inquiry questions path can be accounted for by these instructions. Another reason for pursuing this path is the students' engagement in understanding their inquiry project.

Both the preliminary to major and the major to major paths are characteristic of the open inquiry process, as students perform the next step of the inquiry, based on analysing the previous one. Sadeh and Zion (2012) showed that students performing open inquiry feel involved in their project compared with guided inquiry students. Also, facing the uncertainty inherent to open inquiry leads to higher engagement (Watkins et al. 2018). The high percentage of choosing both these paths might demonstrate the involvement of the students in this study during their inquiry process. For future research, it would be interesting to characterize the students' learning preferences leading to choosing each path of association between inquiry questions.

Paths of logical associations between inquiry questions and inquiry practices used

Effective inquiry learning improves students' understanding and practices (Şimşek and Kabapınar 2010). Our study shows that the different paths of logical associations between inquiry questions, including various ways of formulating and examining inquiry questions within scientific open inquiry projects, are presented along with different inquiry practices. Planning and design inquiry practices were implemented at similar ratios in all paths of logical association between inquiry questions. The planning and design inquiry practices can be considered as part of the 'investigating' activity suggested by the NRC 'spheres of activity', representing the empirical activity – planning the experiments, determining the methods for investigation, performing the experiments, and collecting the data (National Research Council , 2012a). These practices are the basic structures required for planning the inquiry process (Lunetta and Tamir 1979) and are required at all paths. Our results also demonstrated that these practices were implemented at all inquiry processes examined.

In all paths of inquiry, the students evaluated their inquiry results before moving to the next cycle. Processing the data, examining the reliability and validity of the results, interpretation of the data, and concluding for the next cycle of inquiry are all practices required for the 'thinking behind the doing' of the inquiry process (Roberts, Gott, and Glaesser 2010). Practices like these are the basis of understanding evidence (Roberts and Johnson 2015), are included in the analysis and interpretation and in the application types of inquiry practices. In all three paths of logical associations between inquiry questions, these practices were significantly higher than the planning and design inquiry practices. Thus, in all paths, the open inquiry process enables the development of an understanding of the process.

The analysis and interpretation inquiry practices were significantly higher in the preliminary to major path of logical associations between inquiry questions than the other two paths. In this path, the students conduct preliminary experiments, analyse their results, and then formulate the major inquiry question based on their interpretation of the preliminary results. Practices like these can be viewed as part of the 'developing explanations and solutions' part of the NRC spheres of activity. These practices succeed because to go to the next part of the inquiry, the students must develop some explanation or hypothesis, which leads to new questions to be examined (National Research Council , 2012a). In the preliminary to major path of association between inquiry questions, the students must go back to their preliminary results and analyse them before formulating the major inquiry question. A path like this requires the students to analyse and evaluate results and apply them to new situations. Going back and reflecting on one's thinking is a characteristic of critical thinking (Halpern 2001; Niu, Behar-Horenstein, and Garvan 2013). Thus, as our results indicate a relationship between the preliminary to major path and the analysis and interpretation practices, this path of logical association between inquiry questions also engages students in critical thinking.

Application inquiry practices include performances that go beyond the results of the experiments. These practices were higher in the major to major path than in the two other paths. Creative thinking requires several processes, including organizing and analysing information, generating and evaluating new ideas, and planning new solutions (Mumford, Medeiros, and Partlow, 2012). Application practices include making predictions, formulating hypotheses based on the inquiry results, and applying inquiry techniques to new situations, thus being associated with creative thinking. Our results indicate that formulating and examining a major inquiry question supports application practices after formulating and examining a previous major inquiry question; thus, such an inquiry path might also encourage creative thinking.

The major to theoretical path was not particularly associated with any of the categories of inquiry practices examined. In this path, the students perform a long-term inquiry, leading to the formulation of a theoretical inquiry question, which is not examined in the scope of the inquiry project. This result indicates that formulating a theoretical inquiry question might not promote the development of inquiry practices as much as the other paths of logical associations between inquiry questions. The latter paths include hands-on activity throughout the entire inquiry process. Hands-on activities can support science learning. They have meaningful goals and are integrated into the learning activity to include, among other things, data analysis and explanations (National Research Council , 2012b). Our results indicate that in an open inquiry process, in which such activities are integral, performing several iterations of hands-on activity during the inquiry process is required to effectively develop inquiry practices.

Paths of logical associations between inquiry questions and types of knowledge used

Overall, our results indicate that the different paths of logical associations between inquiry questions presented in the bio-inquiry scientific summaries are associated with various types and quality of knowledge. Detailed analysis of the results showed that the preliminary to major path was associated with three types of knowledge: procedural, logical, and strategic. The procedural knowledge quality was significantly higher in the preliminary to major path than in both other paths. Procedural knowledge represents a sequence of actions (de Jong and Ferguson-Hessler 1996). In this path of logical association between inquiry questions, students perform several preliminary experiments. This path compels them to engage in an iterative approach in which each experiment is planned based on understanding the relevant evidence of the previous one. Such an approach is open-ended, and students who conduct such inquires must have good procedural understanding (Roberts, Gott, and Glaesser 2010). Our results are consistent with this, as they indicate that procedural knowledge was used in the preliminary to major path. In this path, engaging in preliminary experiments leads to formulating and examining a major inquiry question.

Logical knowledge was also used in the preliminary to major path. Logical knowledge includes causality, understanding connections, and problem-solving (Farnham-Diggory 1994). This path engages students in inquiry that includes several steps of hands-on activity, which might develop this component of knowledge. In the preliminary to major path, the students formulate inquiry questions, do the research, and examine their results, then formulate and examine another research question. An inquiry process such as this emphasizes the dynamic nature of inquiry and develops logical thinking. Our results are consistent with the previous study, showing that formulating, planning, and examining consequent logically connected inquiry questions requires the development of logical knowledge (Zion et al. 2004).

The third type of knowledge associated with the preliminary to major path is strategic. This knowledge represents the problem-solving processes that direct the stages to a solution and problem-solving practices (McDonnell and Mullally 2016). In the preliminary to major path of inquiry, the students engage in several preliminary experiments and interpret their results, leading to formulating major inquiry question experiments. Our results indicate that engaging in such an inquiry process might deepen this type of knowledge, as students must engage in the problem-solving process several times in the inquiry process.

The major to major path was associated with logical knowledge and situational knowledge. Situational knowledge is domain-specific; it allows extracting information from a problem and later adding to it (Richter-Beuschel, Grass, and Susanne 2018). Formulating and examining a major inquiry question at the first stage of an inquiry project involves the students' deep understanding of this question, thus requiring a deep understanding of the typical situations in that field. This might explain the development of situational knowledge in the major to major path.

Logical knowledge was also used in the major to major path. Like in the preliminary to major path, in the major to major path students perform an inquiry process in which they engage in hands-on activity through several steps of the inquiry. They formulate and examine a second inquiry question following the results of another question. Thus, a path like this involves consequent logically-connected inquiry questions, requiring and developing logical knowledge (Zion et al. 2004). Situational knowledge was used in the major to theoretical path. As was determined in the major to major path, our results indicate that examining a major inquiry question that engages students in a deep understanding of this question requires their understanding of the situation.

Conceptual knowledge includes facts, concepts, and principles required to solve problems (de Jong and Ferguson-Hessler 1996) and enables generating strategies to solve new problems (Aydın and Özgeldi 2019). Conceptual knowledge is required in all open inquiry processes. Thus, although not particularly used in any of the paths of associations between inquiry questions, conceptual knowledge is high in all three paths.

Conclusions

Open inquiry is a major feature of science education in different countries, specifically in high school (Bennett et al. 2018). The current study adds to the body of knowledge concerning the impact of open inquiry projects on students; thus, its conclusions are relevant for the science education community – particularly its teachers and curriculum developers.

Previous studies showed that different types of knowledge and different inquiry practices are developed through engaging in different paths of inquiry (Roberts 2001; Sadeh and Zion 2012). In this study, we demonstrated that groups of students who employ different paths of association between inquiry questions, related to formulating and performing an open inquiry project, use certain inquiry practices and types of knowledge more frequently. Our study specifically showed that in the paths of logical associations between inquiry questions, where the students were engaged in several hands-on activities (e.g. preliminary to major and major to major), they used diverse practices and types of knowledge.

Kapur (2008) refers to productive failure as a learning process that may lead to poor performance in the short term while promoting deep learning in the long run. Students often use processes that include a problem-solving phase that involves them dealing with unfamiliar concepts. In this phase the students rely on their prior knowledge while trying to reach a solution. This reliance on prior knowledge enables them to explore multiple solutions to a novel, complex problem. As such, the students might experience failure and high uncertainty during the learning process. In the following stage, the students have opportunities to compare their work to canonical solutions. The process of independent problem-solving with no prior instruction may also have affective benefits such as high engagement and motivation and learner agency (Kapur 2016). In the bio-inquiry process, specifically in the preliminary to major and the major to major paths, students formulate a major inquiry question only after setting up an experimental system and analysing results, dealing with difficulties, and experiencing different solutions during the inquiry process. Our results indicate that this process promotes knowledge and inquiry practices, representing the gains of the learning process. Thus, we recommend that the students engage in different paths of scientific inquiry processes, preferably those involving several inquiry questions and continuous hands-on activities integrated with planning the inquiry. Activities like these can advance inquiry practices and deepen the knowledge base of high school biology students. In interpreting the results of our study, we recognize the importance of noting its limitations. One limitation is that the study analysis was based on the students' written summaries alone. Accompanying the study with student interviews might have provided a deeper perspective of their conceptions of scientific inquiry based on their learning characteristics. Another limitation is the multitude of post-hoc tests that were calculated, leading to an inflation of the alpha level.

The results of the current study raise issues for further investigation. These include whether the types and quality of knowledge employed during the learning process can be enhanced by instructing the students to explain the logical association between inquiry questions. Another issue is whether the inquiry practices and types of knowledge employed by the students can be deepened and expanded by guiding them to perform several stages of hands-on activity. We suggest that future studies would focus on these matters. Furthermore, the current study examined the knowledge and practices of groups of students. A future study might consider the individual development of students within these groups. Finally, this study analysed scientific summaries of open inquiry processes, not the process itself. It would be of interest to track the students' development during the inquiry process itself.

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APPENDIX 1

Inquiry practices demonstrated in associations between inquiry questions in the scientific summaries and examples of categorization of inquiry practices

APPENDIX 1a.

Inquiry practices demonstrated in associations between inquiry questions in the scientific summaries.

Characterization of inquiry practices required for the association between inquiry questions	Level of application of the inquiry practice in the scientific summary
Planning and design Analysis and interpretation Application	1 – not mentioned or not clear 2 – mentioned but not well explained 3 – mentioned and well explained

APPENDIX 1b.

Examples of categorization of inquiry practices. The examples presented in this table are paraphrases of student-written original materials.

Category	Level of application of the inquiry practice
Planning and design	In light of this, our assumption for the first inquiry question is that wheat develops most effectively when chemical fertilizer is applied in concentrations that accord with manufacturer recommendations. This assumption is based on the fact that the use of concentrations of chemical fertilizer that significantly exceed recommended amounts produces negative effects, ranging from leaf burning to plant death. After we examine the first inquiry question, we will continue our inquiry by examining the influence of different nitrogen concentrations on wheat development – when we examined the composition of the fertilizer we used, we found that nitrogen is the main component (10%). The second inquiry question will be to determine the influence of different concentrations of nitrogen on wheat development. In the experiment, we will germinate wheat seeds and then water them with different nitrogen concentrations. We used the nitrogen concentrations shown by Friedlander (2003). 2 – mentioned but not well explained
Analysis and interpretation	Our inquiry question was: What is the influence of the mallow leaf diameter on the rate of photosynthesis? Our experiment showed unpredictable results; the leaves with the largest diameter showed the lowest rate of photosynthesis. In light of this, we built the following inquiry question to examine this phenomenon: What is the influence of size and shape of different leaves (peppermint, parsley, dill, basil, lemongrass) on the rate of photosynthesis? We speculate that the smaller the leaf diameter is, the higher the photosynthesis rate will be. 3 – mentioned and well explained

APPENDIX 2

Types and quality of knowledge demonstrated in associations between inquiry questions in the scientific summaries and examples of categorization of types and quality of knowledge

APPENDIX 2a.

Types and quality of knowledge demonstrated in associations between inquiry questions in the scientific summaries.

Type of knowledge	Level of knowledge	Structure of knowledge	Quality of knowledge for problem-solving
Procedural knowledge Conceptual knowledge Logicalknowledge Situational knowledge Strategic knowledge	1 – surface 2 – deep	1 – isolated elements 2 – loosely connected 3 – structured knowledge	1 – general steps for defining the problem components 2 – specific steps for defining the problem components

APPENDIX 2b.

Examples of categorization of types of knowledge. The examples presented in this table are paraphrases of student-written original materials.

Type of knowledge	Quality of knowledge
Procedural knowledge	The phenomenon we examined was the influence of environmental conditions on the growth of mold on various food products. For our experiments, we used fruits with sugar concentrations that are close to 17.5%, such as persimmon (18.6%), orange (13.6%), and mango (17%) (http://www.metukim.co.il). We concluded that when fruits with those sugar concentrations are stored in a relatively high-temperature environment, the rate of mold development will be higher than if they were stored under refrigeration. To delay the growth of mold on fruit, based on our experiments, they should be refrigerated. Fruit with high sugar concentrations is subject to quicker acceleration of black mold growth when it is unrefrigerated. Level: 1 – sporadic Structure: 3 – structured Quality for problem-solving: 2 – specific steps
Situational knowledge	In our experiment, we chose to examine the phenomenon of bubbles that appear during the dough-rising process. Prior knowledge informs us that dough rises as a result of the cellular respiration of its yeast component. We were interested in whether we could find a method to improve the efficiency of the process. We decided to examine what would happen if we use different kinds of sugar to replace the sucrose that is generally used. Another factor that can influence the cellular respiration of yeast is the presence of a detergent. We considered the possibility that the dishes used for baking might contain residues of the detergent used for washing them. We wanted to examine whether detergent would influence dough rising. Our second inquiry question sought to determine the influence of detergent on the rate of cellular respiration of yeast. The biological base for our speculation is that adding detergent to yeast will damage the cell membranes of the yeast. That is because the detergent includes components that melt the phospholipids of the cell membrane. When the phospholipids of the cell membrane are destroyed, their selectivity is compromised. Level: 1 – sporadic Structure: 2 – loosely connected Quality for problem-solving: 1 – general steps