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ARTICLE

Comparing the Impact of Two Science-as-Inquiry Methods on the NOS Understanding of High-School Biology Students

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Abstract
The current study compared the effectiveness of two methods in biology teaching that are based on the science-as-inquiry approach: visits to authentic university laboratories (AULs) and analyzing adapted primary literature (APL). The methods' effectiveness was measured in terms of high-school students' increased understanding following a 6-week intervention that emphasized five major aspects of the nature of science (NOS): the tentativeness of scientific understanding, the cooperative nature of the scientific process, methodological diversity, the sociocultural embeddedness of scientific knowledge, and the aims of scientific inquiry. A quasi-experimental, pre-post control design was applied, utilizing quantitative evaluation methods. Findings indicate that teaching NOS in biology high-school classes using science-as-inquiry methods is an effective approach for enhancing NOS understanding. Both of the proposed methods appear to be promising; however, the AUL method was found to be more effective for enabling advanced-level high-school biology students' understanding of these NOS aspects. In conclusion, both AUL and APL are potentially effective methods that can be adapted for teaching various biology subjects in different cultural contexts.

1 Introduction

Teaching the nature of science (NOS) is an essential element of the science curriculum in many countries including the USA (NRC 2012; NGSS Lead States 2013) and Israel (Israeli Ministry of Education 2010). Many studies conducted in this field have demonstrated the importance of including NOS in school science syllabuses (see for example, Lederman 1992; McComas 1998; Matthews 2014). Nonetheless, a debate exists over the best instructional methods for teaching NOS. One of the approaches to teaching NOS is "teaching science as inquiry" (Chiappetta 1997; Tamir 1976, 1989, 1990). This approach is based on studies by Schwab (1958, 1962, 1963, 1966, 2000), which stress "enquiry into enquiry" as an optimal approach to promoting inquiry learning, claiming that "the complete enquiring classroom would have two aspects. On the one hand it

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would exhibit science as enquiry. On the other hand, the student would be led to enquire into these materials" (Schwab 1962, p. 65). Schwab emphasized that the teaching process should favor an "active learning in which lecture and textbook are challenged […] become materials to be dissected, analyzed" (p.66). The advantage of this approach, according to Schwab (1964), is that it exposes students to two structures that are characteristic of the disciplines of science, namely, substantive and syntactical structures. The substantive structure determines the frame of knowledge, the questions that are asked, the data sources, the type of experiments conducted, and the way the conclusions are drawn. The syntactical structure of each discipline encompasses the methodologies, instruments, and criteria that are unique to each discipline and which determine the ways in which ideas are developed.

A variety of instructional methods have been used in the context of this approach, including integrating the teaching of history and philosophy of science (Galili 2012; Galili and Hazan 2001), discussions of socioscientific issues (Lederman et al. 2014; Tal and Kedmi 2006) or contemporary cases (Allchin et al. 2014). All of these methods are intended to expose students to the manner in which scientists interpret information and draw conclusions. At the same time, they present science as a human activity for constructing *tentative* but *objective* knowledge, i.e., a rational account of Nature (Galili 2012).

The goal of this study was to compare the effects of two science-as-inquiry methods for teaching biology in high school in terms of students' understanding of NOS. The two methods are visiting authentic university labs (AULs) and reading and analyzing adapted primary literature (APL).

1.1 Aspects of NOS

Ever since NOS has been included in the syllabuses of high-school science lessons, there have been numerous suggestions in the professional literature regarding which aspects of NOS should be taught. Lederman (1992, 1999), Lederman and Lederman (2004), McComas (1998, 2004, 2008), and Osborne et al. (2003) have suggested rather similar "key NOS aspects" that should be studied in school. McComas (2017) provided a "widely-shared consensus proposal of NOS elements" (p. 73) arranged in three clusters with related sub-elements:

1. "Science knowledge and its limits"—science is distinct from technology and engineering; science is tentative but durable; science cannot address all questions.
2. "Tools and products of science"—empirical evidence is required; science shares methods; law/theory distinction.
3. "Human elements of science"—creativity is vital in science; subjectivity is a frequent element in science; social and cultural elements impact science.

However, some science educators (Allchin 2011; Clough 2011; Dagher and Erduran 2016; Erduran and Dagher 2014; Irzik and Nola 2014; Matthews 2012) have criticized this "consensus view." Matthews (2012) proposed to replace the term "nature of science" with "a more relaxed, contextual and heterogeneous 'features of science'" (p. 4). Promoting elaboration, inquiry and discussion by focusing on the features of sciences is intended to avoid the memorization of a number of NOS tenets. Additionally, he underscores the importance of discussing and reflecting on the complex nature of the NOS aspects, especially when teaching high-school students. Kampourakis (2016) proposed a resolution of these debates, suggesting that the "'general aspects' conceptualization of NOS provides an effective starting point for teaching about NOS and for addressing students' preconceptions about science. Once this is done, teaching could include more complex aspects and attend simultaneously to multiple contexts, as the critics suggest" (p. 667). Bearing in mind this suggestion, I have outlined five major NOS aspects, which, in line with Schwab's (1962) perspective, adapted and broadened the aspects set forth in the NGSS (NGSS Lead States 2013) and in the Israeli Biology Curriculum (Israeli Ministry of Education 2010, 2017). Focusing on these five NOS aspects ensured the inclusion of the sociological, historical, and philosophical perspectives, as well as those of contemporary scientists. Furthermore, the five aspects referred to in this study correspond to the substantive and the syntactic structures of biology (Schwab 1964). In the current context, for example, students compared cell-biology research and field-based ecological research using the selected NOS aspects. Thus, these aspects served as a tool for discussing both the processes that guide biological inquiry in general, as well as the principles and the terminology used in each field, while drawing a distinction between the two structures.

The following is a list of the five NOS aspects used in this study:

1. *Tentativeness*. Scientific knowledge, although reliable and durable, is never absolute. It is subject to change, as new theoretical and empirical evidence supports or challenges the available knowledge. In the current study, the objective was to lead students to the realization that tentativeness is a positive feature of science, and that knowledge accumulation and/or the overturning of theories are steps towards greater validity.
2. *The cooperative nature of science*. Too often, popular media portrays scientists as lone (male) techies investigating "ridiculous scientific premises" (Moody and Kirschenbaum 2009, p. 82). Such depictions could cause media consumers to misunderstand the nature of scientific research, given that they fail to recognize that scientific cooperation aids in establishing reliability and validity (Driver et al. 1996). In the current study, the objective was to lead students to the understanding that science is, more often than not, carried out by groups of researchers, and that each group is linked to a larger network that shares common research interests. Well-established procedures regulate information sharing via conferences and journals, while the peer-review process controls which findings are transformed into public knowledge.
3. *Methodological diversity*. A widely held NOS-related misconception is that there exists a single, monolithic, linear, "scientific method" that is used to conduct research. This notion has been discredited by scientists and philosophers (Cartwright 1999; Cleland 2002; Diamond 2002), as well as by science-education researchers (Gray 2014; Lederman et al. 2002). Science is characterized by methodological diversity, with numerous scientists investigating a specific phenomenon using various tools and strategies. Based on philosophical and empirical support found in the professional literature (Dodick et al. 2009), the intervention of the current study emphasizes the distinction between two particular methods: experimental (e.g., cell biology) and field-based (e.g., field-based ecology) sciences, thus providing students with a concrete example of methodological diversity.
4. *The sociocultural embeddedness of scientific knowledge*. Abd-El-Khalick (2012) posited that as a human endeavor, science is by definition embedded and practiced within the larger context of the local and temporal cultural milieu. In the current study, this NOS aspect was meant to clarify that scientific activity cannot be divorced from personal agendas or from cultural, social, and economic contexts.
5. *The aims of scientific inquiry*. This deals with the relationship between two types of research: "basic research" and "applied research." In the current study, the goal was to expand students' understanding of the mutual relationship between basic and applied research.

1.2 Teaching of Science as Inquiry in the Context of Biology Education

Inquiry learning has been classified as "learning as inquiry" and "learning by inquiry" (Tamir 1985; Chiappetta 1997). Learning by inquiry involves the students in "doing science," in performing the "scientific practices" (NRC 2012; NGSS Lead States 2013). Learning as inquiry has been suggested to be learning about the way in which the scientific endeavor takes place, and analyzing the inquiry process performed by others (Tamir 1985; Falk et al. 2008). With this distinction in mind, Allchin et al. (2014) proposed to integrate the "complementary approaches" by combining student inquiry, historical cases, and contemporary cases.

Schwab (1962) proposed three methods for teaching biology using the science-as-inquiry approach, methods which expose the learner to the processes of scientific research through reading and analysis. As will be explained in greater detail later, the following three methods have been integrated—in one form or another—into the field of biology teaching in Israel and elsewhere.

1. "Invitations to Enquiry": small segments of text presenting individual parts of research accompanied by questions and assignments (Schwab 1962, p.95).
2. "Narrative of Enquiry": a description of a series of research projects devoted to the same theme, such as cases of research from the history of science (Schwab 1962, p.87).
3. "Original scientific papers": original scientific studies from scientific publications (Schwab 1962, p.73).

The method of reading and analyzing historical narratives has been particularly well received among researchers concerned with NOS teaching (Abd-El-Khalick and Lederman 2000; Allchin 2012; Allchin et al. 2014; Dass 2005; Galili and Hazan 2001; Irwin 2000; Kampourakis 2013; Kampourakis and McComas 2010; Kampourakis and Gripiotis 2015; Kim and Irving 2010; McComas and Kampourakis 2015). Furthermore, it was found to have a positive effect on biology students' NOS understanding (e.g., Campanile et al. 2015; Faria et al. 2012; Howe and Rudge 2005).

An additional method used in biology teaching, which can be included in the "science as inquiry" approach, involves reading, analysis, and discussion of socioscientific issues [SSI], (Abd-El-Khalick 2003; Allchin et al. 2014; Klosterman and Sadler 2010; Sadler et al. 2004; Tal and Kedmi 2006; Wong et al. 2008; Wong et al. 2011). Reports have indicated that this method stimulates biology students' understanding of NOS (see for example, Eastwood et al. 2012; Khishfe 2014; Lederman et al. 2014; Sadler et al. 2004).

In Israel, the first two of the three abovementioned methods introduced by Schwab (1962) were incorporated in biology teaching in the 1970s (Tamir 1976, 1989) and still form an integral part of teaching materials and textbooks for teaching biology (National Center for Biology Teachers 2018). The third method, i.e., reading original publications of scientific studies, was developed into the APL format and, since 2002, it has been part of the program for biology studies in Israel (Israeli Ministry of Education 2003, 2010). More recently, the AUL method (Tsybulsky et al. 2017a, b) was developed, as an elaboration of the "narrative of enquiry" method, and is currently being applied as an enrichment program for high-school biology students. The focus of the current study is on these two methods, the APL and the AUL; hence, an in-depth description of them follows.

The AUL method was originally developed for a high-school biology outreach program, the primary goals of which were to enhance students' understanding of NOS and to improve their attitude towards science (Tsybulsky et al. 2017a). This method involves students' visits to university research laboratories, and stresses the dialog between students and researchers on NOS aspects. A 3-year research study showed that the AUL method does indeed have a positive effect on students' NOS understanding (Tsybulsky et al. 2017a, b).

The APL method was developed by Yarden et al. (2001) and is included in the Israeli biology curriculum in the context of one of the elective topics that high-school teachers can choose to include in their syllabuses (Israeli Ministry of Education 2010; Yarden et al. 2001). APL refers to an educational method specifically designed to enable published research articles to be used in the framework of biology teaching in high school. The APL method has been shown to improve students' understanding of the nature of scientific inquiry and to develop their ability to scientifically critique the work of other science researchers (Baram-Tsabari and Yarden 2005).

The APL and AUL methods involve different types of *authenticity*. The term *authenticity* has various meanings (Yarden and Carvalho 2011). In the current study, *authenticity* is defined in the context of the learning environment, as follows. AUL combines two types of learning environments: the formal school framework and the non-formal, authentic research environment of science laboratories, which includes direct contact with scientists. APL is used solely in a formal framework (schools) and includes indirect contact with scientists (via texts).

The question that motivated this study was whether these two methods equally affect students' NOS understanding. To this end, the study was designed to measure and compare the effects of both the APL and the AUL methods on students' NOS understanding.

2 Methods

2.1 Design and Implementation of the Two Versions of the Learning Unit

To assess and compare the effect of the two methods on students' NOS understanding, two versions of a high-school biology study unit were designed, implemented, and evaluated. The title of the selected unit was *Students Meet Authentic Science*. Version 1 of the unit was based on the AUL method, while version 2 was based on the APL method.

Both versions of the unit were intended for high-school students (in the 11th grade, age 16–17) enrolled in the highest level of biology studies (i.e., students studying for maximum credit points in the Israeli matriculation exams). The contents of the unit are directly related to the biology curriculum, in that they focus on two core issues: cell biology and ecology.

Each version of the unit spanned a total of 14 h and comprised three stages: (i) preparation, (ii) main activity (the laboratory visits in version 1 or reading of articles in version 2), and (iii) summary. The preparation and summary stages were identical in the two versions and also included science-as-inquiry teaching methods (including both narratives of inquiry and historical narratives). This parallel structure was designed to strengthen the impact of each method on the students' NOS understanding. In addition, this parallel design enabled us to compare the two methods using standard quantitative research methods, as the main and most substantial difference between them was confined to the second stage, involving either the laboratory visits or readings.

For each version, a distinct student manual was prepared, which presented the materials for the respective study unit and included space for the students to write in (for the stages in which they were expected to answer questions or record their own reflective analysis).

2.2 Version 1: Implementing the AUL Method

Stage 1—Preparation (duration: approximately 6 h in class). This stage included a multimedia presentation introducing the laboratories and the research staff that the students would visit, as well as the questions that the research conducted by each particular laboratory was intended to address, the respective research methods, and the relevant equipment. The reading materials about the research topics of each laboratory were prepared and formatted according to Schwab's "narratives of enquiry."

Also in the preparatory stage, the students prepared (in small groups) questions to ask their guides during the laboratory visits. This is a critical component, which demands cognitive and emotional preparation on the part of students, as they come to understand that during the visits they are expected to take on an active role, that they are responsible for their learning, and that the field trip is intended for more than their general amusement. The students received clear instructions from their teachers on how to prepare written questions for the researchers. They were encouraged to ask questions that interested them regarding the subject matter, as well as to raise questions and challenges regarding the research methods and the research processes themselves.

Stage 2—Laboratory visits (duration: approximately 4 h). The lab visits comprised the central component of the learning process in the AUL unit; the visit to laboratories located outside the school facilities took place between the two in-class sessions, which were designed to enhance students' experience during the visits. In the current study, the students who participated in version 1 visited two laboratories, each for 2 h, on the same day: one specializing in cell biology and the other in ecology. A graduate student in each lab guided the students, describing his or her own research in the context of the designated aspects of NOS, thus providing an *authentic narrative of inquiry*. The guide also responded to the students' prepared questions and led a broader discussion.

Stage 3—Summary (duration: approximately 4 h, in class). The students, led by their teacher, wrote reflective comparisons about the two labs they had visited, and discussed these in class. The following are examples of discussion topics addressed:

Could researchers change their minds about the factors that influence stem-cell growth/ species extinction (tentativeness)?

Are the same methods used to conduct research on stem cells and species variability (methodological diversity)?

Could stem cell research and species variability studies be conducted in the USA (sociocultural embeddedness)?

Did the scientist whom you met in each of the labs work alone/in a group/in cooperation with other scientists in Israel and abroad (cooperative nature of the science)?

Could the two examples of research be considered applied research (aims of scientific inquiry)?

Students also extended their NOS learning by reading and discussing a *historical narrative* describing how a model for DNA structure had been proposed, which was included in the student manual that was designed for the unit. The reading was followed by questions that focused explicitly on the NOS aspects taught in this unit, for example:

- What did the scientific community think about the source of genetic material before the discovery of DNA (tentativeness)?
- Is the study by Watson and Crick an example of basic research or of applied research (aims of scientific inquiry)?
- Is the discovery of DNA an example of collaborative and cooperative research (in light of Rosalind Franklin's role)?
- Were there social, economic or governmental factors that influenced the study of DNA (sociocultural embeddedness)?
- What research methods were used in the study of DNA (methodological diversity)?

2.3 Version 2: Implementing the APL Method

As noted above, the preparation and summary parts of this study unit were more or less identical to those used in version 1. The middle part of this version included reading and analyzing APL (instead of visiting research laboratories). Up-to-date scientific papers written and published by researchers working at the Hebrew University of Jerusalem were adapted and translated into Hebrew. The adaptation process did not alter the canonical structure of the research article or the original results, but adapted the contents to match high-school students' comprehension level. The process of adapting the scientific articles was based on Yarden et al.' (2001) study and included the following changes: the Introduction section of the articles was modified to give the novice reader basic background information that was either omitted or simply quoted from the original paper; the main principles of the Methods sections were described, while omitting details of amounts, solution compositions, and so on; the Results section remained unchanged, although secondary implications that diverged from the main research question were omitted; the main figures were kept, with only slight modifications; and, finally, the Discussion section was expanded so that students could understand it more easily.

The students read two papers: one in cell biology and one in ecology. The abstracts of the papers are presented in Appendix 1. Both during and after the readings, they answered the questions in their manual (which mostly focused on the five NOS aspects). The APL implementation included the following three steps: (1) the students read the Cell Biology article and individually answered the subject- and NOS-related questions and then the teacher led a classroom discussion around these questions; (2) the students read the Ecology article, individually answered the subject- and NOS-related questions and the teacher led the classroom discussion around these questions; (3) the students were asked to compare the two articles, and then, a classroom discussion was led by the teacher.

The following are examples of the NOS-related questions related to the articles:

- Is this study an example of basic research or of applied research?
- Was the study conducted collaboratively or individually?
- What are the implications of this study?
- What methods were used (consider the subjects, the procedure, the hypotheses and the type of results predicted, and the validation)?
- Could the researchers change their mind about the factors that influence stem-cell growth/species extinction?
- Could the studies be conducted in any country in the world?

2.4 Sample and Research Context

The sample consisted of 210 students in grade 11, ages 16–17, from a high-to-mid-level socio-economic background, attending schools in Jerusalem, Israel, and who were enrolled in the advanced high-school biology program, with core studies in physiology, cell biology, and ecology. This sample was selected, because the participants had some background in biology studies (from their studies in grade 10, the first year of the advanced high-school biology program), and because, unlike 12th graders, they were not under the pressures of upcoming matriculation exams and/or involvement in the "Bio-Investigate" program. In the advanced biology program, the focus of the 10th grade curriculum is on human biology (emphasis on physiology); in the 11th grade, the focus of the first semester is on cell biology and that of the second semester is on ecology. The study was implemented during the months of April and May, i.e., towards the end of the school year, so that by then, students were familiar with the study material on these two major topics (i.e., cell biology and ecology). In other words, the intervention was not their first encounter with the material, concepts, and terminology of these two fields. This timing of the intervention units in the academic year was intended to minimize students' experience of "novelty in the cognitive domain" (Orion and Hofstein 1994). Thus, students had sufficient knowledge of the ideas and concepts in each field that enabled them to read the adapted scholarly articles and understand explanations of the research conducted at the university labs. The underlying intent was to make narrower the gap between the knowledge and lingo of the researchers (whether encountered as authors or as scientists) and the knowledge and lingo available to the students.

The study employed three research groups: (a) experimental group 1 ($n = 75$; male students = 29, female students = 46)—students who learned according to Version 1 of the study unit (the AUL method); (b) experimental group 2 ($n = 64$; male students = 21, female students = 43)—students who learned according to version 2 of the study unit (APL method); and (c) control group ($n = 71$; male students = 23, female students = 48)—students who learned according to the standard biology program (cell biology and ecology), without the use of science-as-inquiry teaching methods (see Table 1, which summarizes the differences between the methods used in each group). All of the students signed informed consent forms, indicating the voluntary nature of their participation in this study.

2.5 Instruments and Data Collection

To evaluate and compare the effects of the AUL and the APL methods on students' NOS understanding, a quasi-experimental, pre-post control design was applied, which utilized quantitative evaluation methods. Participants completed a questionnaire that examined students' understanding of the five NOS aspects specified, each of which was represented in the questionnaire by two Likert-like items. For each Likert-ranked item, a section was added in which participants were asked to explain their choice, using an open-ended format. Thus, the questionnaire included ten Likert-like items, to which participants responded indicating their agreement on a scale ranging from 1 (= "I disagree completely") to 10 (= "I agree completely"). The questionnaire's validity and reliability had been established previously by two different means. First, individual interviews were conducted with several students, to assess whether the statements were clearly understood by the students and whether the students' responses to the open questions provided the type of information needed for the purpose of the study (for details, see Tsybulsky et al. 2017a). The second means was to examine the internal reliability of the questionnaire, which was found to be 0.8 Cronbach's alpha.

Table 1 Comparison of the teaching method used with each of the three research groups

Feature	Control group	Exp. group 1 [AUL]	Exp. group 2 [APL]
Learning environment	Class	Class and university research labs	Class
Learning mediators	Teachers	Teachers and graduate students	Teachers
Teaching method	Biology instruction without science as inquiry teaching methods	Biology instruction using AUL method	Biology instruction using APL method

The experimental groups and the control group completed the same questionnaire before and after participating in the respective versions of the study unit, which typically meant an interval of 6 weeks.

2.6 Data Analysis

2.6.1 Likert-Like Items

Statistical analysis of the Likert-like items was conducted using non-parametric, Wilcoxon signed-rank and Sign statistical tests. To compare the effects of the teaching methods on the three participant groups, two types of comparisons were conducted: (a) pre- and post-intragroup comparisons, and (b) pre- and post-intergroup comparisons.

2.6.2 Open-Ended Responses

Analysis of the open-ended responses (in which students explained their choice of response to the Likert-like items) was conducted as follows. First, a categorical analysis was conducted, which involved assigning responses to one of three categories: *inadequate*, *adequate*, or *informed*. Explanations that showed complete understanding of the NOS aspects, with several examples and extensive explanations were categorized as *informed*. Responses that demonstrated a developing understanding but lacked in-depth explanations or examples were categorized as *adequate*. The category *inadequate* corresponded to responses that contained a misconception. Appendix Table 6 contains examples of responses corresponding to the three categories and related to each of the five NOS aspects.

An inter-rater reliability of 97% was achieved via comparisons between the author and an outside rater. Only responses categorized as *informed* were included in the comparative analysis. Qualitative categories were then transformed quantitatively into percentages. To assess the p values of changes in students' pre- and post-understanding of NOS aspects, two types of comparison were conducted: (a) pre- and post-intragroup comparisons were conducted using chi-square tests; (b) pre- and post-intergroup comparisons were conducted using 2×2 contingency analyses, while applying the Bonferroni correction where applicable.

3 Results

The findings of the intragroup comparison of Likert-like scores of the research groups, calculated as post-minus-pre differences are presented in Table 2.

An examination of the findings shows that in the experimental group 1 (AUL), the pre-post differences were significant in all NOS aspects, indicating that students who studied in the

Table 2 Research groups' median scores on Likert questionnaire at pre- and post-intervention, and intragroup differences

Aspects of NOS	Questionnaire statement*	Exp. group 1			Exp. group 2			Control group		
		Pre median	Post median	Median differences (of post-minus-pre scores)	Pre median	Post median	Median differences (of post-minus-pre scores)	Pre median	Post median	Median differences (of post-minus-pre scores)
1. Tentativeness	(a) Modern scientific knowledge is better able to explain natural phenomena than knowledge from previous years.	5	6	1**	5	6	1**	5	5	0
	(b) Scientific knowledge is true, accurate, and does not change over time.	5	4	− 1**	5	4	− 1**	5	5	0
2. Cooperative nature of science	(a) Scientists maintain a dialog with one another, rather than working in isolation.	6	8	2**	6	7	1	6	6	0
	(b) Scientists rarely share their results with other researchers.	4	3	− 1**	4	4	0	4	4	0
3. Methodological diversity	(a) In the natural sciences, there is a universal scientific method common to all fields of research.	7	4	− 3**	6	4	− 2**	6	6	0
	(b) Ecology and cell biology use the same methodology of scientific research.	7	4	− 3**	6	4	− 2**	7	7	0
4. Sociocultural embeddedness	(a) Scientists are not affected by any outside authority (government, society, ethics, etc.).	6	5	− 1**	7	6	1	7	7	0
	(b) The work of scientists is influenced by society and culture.	5	7	− 2**	5	5	0	4	4	0
5. Aims of science	(a) Scientific research should be conducted only when there is a high probability that the results will lead to practical developments in the near or distant future.	9	6	− 3**	9	8	− 1	9	9	0
	(b) Technological developments can lead to breakthroughs in basic research.	8	9	1**	8	8	0	8	8	0

*Statements 1b, 3a, 3b, 4a, and 5a are negatively worded and must be interpreted accordingly

**The differences between post-minus-pre scores in the group are significant at least $p = .05$, based on the Wilcoxon signed-rank test

AUL method experienced a significant improvement in their NOS understanding. By comparison, in the experimental group 2, significant pre-post differences were indicated in only two NOS aspects (the tentativeness of scientific understanding and the methodological diversity of scientific inquiry), suggesting that their NOS understanding improved only partially. In the control group, no significant differences were found.

The findings of the statistical analysis of intragroup post- vs. pre-intervention differences pertaining to the subcategory of open-ended informed responses are presented in Table 3. Given that no significant intragroup differences were found in the control group, only the results of the two experimental groups are presented.

A review of the findings indicates that in experimental group 1 (AUL), a significant difference was found between the pre- and post-intervention open-ended informed responses in all NOS aspects. By contrast, in the experimental group 2 (APL), significant differences between the pre- and post-intervention open-ended informed responses were found only in the NOS aspects of the tentativeness of scientific understanding. However, in group 2, for three of the NOS aspects (the cooperative nature of the scientific process, methodological diversity, and the aim of scientific inquiry), there was a significant pre-post difference on at least one of the two items.

The findings of the intergroup comparison of Likert-like scores, calculated as post-minus-pre differences, are presented in Table 4.

A significant difference was found between experimental group 1 (AUL) and the control group on all examined NOS aspects. This finding indicates that the NOS understandings of

Table 3 Statistical analysis of intragroup differences on responses to open-ended questions (*informed* responses only)

Aspects of NOS	Questionnaire statement	Subcategory comparison*	
		Exp. group 1 Post- vs. pre-intervention *p*	Exp. group 2 Post- vs. pre-intervention *p*
1. Tentativeness	(a) Modern scientific knowledge is better able to explain natural phenomena than knowledge from previous years.	.0002	.0004
	(b) Scientific knowledge is true, accurate and does not change over time.	.0002	.0001
2. Cooperative nature of science	(a) Scientists maintain a dialog with one another, rather than working in isolation.	.0001	ns
	(b) Scientists rarely share their results with other researchers.	.0003	.0004
3. Methodological diversity	(a) In the natural sciences there is a universal scientific method common to all fields of research.	.0001	ns
	(b) Ecology and cell biology use the same methodology of scientific research.	.0001	.0001
4. Sociocultural embeddedness	(a) Scientists are not affected by any outside authority (government, society, ethics, etc.).	.0003	ns
	(b) The work of scientists is influenced by society and culture.	.0002	ns
5. Aims of science	(a) Scientific research should be conducted only when there is a high probability that the results will lead to practical developments in the near or distant future.	.0001	ns
	(b) Technological developments can lead to breakthroughs in basic research.	.0001	.0002

*Data are presented for sub-category of "informed" responses, using chi-square test

Table 4 Statistical analysis of Likert questionnaire outcomes: intergroup comparisons

Aspects of NOS	Likert questionnaire statement*	Exp. group 1 vs. control group		Exp. group 2 vs. control group		Exp. Group 1 vs. Exp. Group 2	
		Wilcoxon test *p*	Sign test *p*	Wilcoxon test *p*	Sign test *p*	Wilcoxon test p	Sign test *p*
1. Tentativeness	(a) Modern scientific knowledge is better able to explain natural phenomena than knowledge from previous years.	.05	.05	.05	.05	.05	ns
	(b) Scientific knowledge is true, accurate and does not change over time.	.04	.04	.05	.05	ns	ns
2. Cooperative nature of science	(a) Scientists maintain a dialog with one another, rather than working in isolation.	.05	.05	ns	ns	.05	.05
	(b) Scientists rarely share their results with other researchers.	.05	.05	ns	ns	.05	.05
3. Methodological diversity	(a) In the natural sciences, there is a universal scientific method common to all fields of research.	.02	.01	.05	.05	.05	.04
	(b) Ecology and cell biology use the same methodology of scientific research.	.02	.01	.05	ns	.05	.04
4. Sociocultural embeddedness	(a) Scientists are not affected by any outside authority (government, society, ethics, etc.).	.05	.04	ns	ns	.04	.04
	(b) The work of scientists is influenced by society and culture.	.02	.02	.05	ns	.05	.05
5. Aims of science	(a) Scientific research should be conducted only when there is a high probability the results will lead to practical developments in the near or distant future.	.01	.01	ns	ns	.05	.05
	(b) Technological developments can lead to breakthroughs in basic research.	.05	.05	ns	ns	.05	.05

*Statements 1b, 3a, 3b, 4a, and 5a are negatively worded and must be interpreted accordingly students whose study program included visits to university laboratories improved significantly compared to the NOS understanding of students who participated in the standard biology study program. In contrast, a comparison between the outcomes of experimental group 2 (APL) and the control group rendered a significant difference in only two NOS aspects: the tentativeness of scientific understanding and the methodological diversity of scientific inquiry. On the category of the sociocultural embeddedness of scientific knowledge, a significant difference was found on only one of the two relevant items, and no significant difference was found on either the category of the cooperative nature of the scientific process or on the aims of scientific inquiry. These findings indicate that the NOS understanding of students whose program included reading of adapted scientific articles improved only partially, in comparison to the improvement demonstrated by students who participated in the standard biology study program.

A comparison of the outcomes of experimental groups 1 and 2 found a significant difference on both items pertaining to the following four NOS aspects: the cooperative nature of science, methodological diversity, the aims of scientific inquiry, and the tentativeness of scientific understanding. On the latter category, a significant difference was found on only one of the two Likert-like items. This finding indicates that a greater improvement was achieved in the NOS understandings of students who studied according to the AUL method, compared to changes in the NOS understanding of students who studied using the APL method.

The findings of the statistical analysis of intergroup differences in students' responses to open-ended questions are provided in Table 5. The intergroup pre- and post-comparisons regarding participants' NOS understanding included only the responses that matched the category of *informed*, using a 2×2 contingency analysis test.

The findings indicate that in the experimental group 1 (AUL), significant changes occurred in all of the examined NOS aspects, as compared to the changes in the control group. In the experimental group 2, significant change was noted on two NOS aspects (the tentativeness of scientific knowledge and methodological diversity), as compared to the control group. In addition, in group 1, in two of the NOS aspects (methodological diversity and the aim of scientific inquiry), there was a significant pre-post difference on at least one of the two items. The comparison between findings from experimental groups 1 and 2 showed significant differences on all examined NOS aspects (with the exception of the tentativeness of scientific understanding, in which a significant difference was found on only one of the two corresponding items). This finding shows that the AUL method was more effective than the APL method in influencing students' NOS understanding.

To summarize, the findings indicated that students who studied according to the AUL method improved their NOS understandings both in terms of pre- and post-intervention intragroup comparisons, and in comparison to students who studied according to either the APL method or the standard biology program. The improvement in NOS understanding among students who studied using the APL method was only partial, as indicated by the results of both the intragroup and the intergroup comparisons.

4 Discussion

The goal of the current study was to assess and compare the effects of AUL and APL teaching methods on students' understanding of NOS aspects. Results indicate that both of the methods examined herein had a positive effect on students' NOS understanding. In particular, the findings support the results of a previous study (Tsybulsky et al. 2017a), which indicated that

Table 5 Statistical analysis of intergroup differences on responses to open-ended questions (*informed* responses only)

Aspects of NOS categories	Questionnaire statement	Subcategory comparison*		
		Exp. group 1 vs. control group	Exp. group 2 vs. control group	Exp. group 1 vs. exp. group 2
1. Tentativeness	(a) Modern scientific knowledge is better able to explain natural phenomena than knowledge from previous years.	.0001	.0001	ns
	(b) Scientific knowledge is true, accurate and does not change over time.	.0001	.0001	.0005
2. Cooperative nature of science	(a) Scientists maintain a dialog with one another, rather than working in isolation.	.0001	ns	.0001
	(b) Scientists rarely share their results with other researchers.	.0001	.0002	.0005
3. Methodological diversity	(a) In the natural sciences, there is a universal scientific method common to all fields of research.	.0001	.0004	.0003
	(b) Ecology and cell biology use the same methodology of scientific research.	.0001	.0002	.0005
4. Sociocultural embeddedness	(a) Scientists are not affected by any outside authority (government, society, ethics, etc.).	.0001	ns	.0001
	(b) The work of scientists is influenced by society and culture.	.0001	ns	.0001
5. Aims of science	(a) Scientific research should be conducted only when there is a high probability that the results will lead to practical developments in the near or distant future.	.0001	ns	.0001
	(b) Technological developments can lead to breakthroughs in basic research.	.0001	.0005	.0004

*Data are presented for sub-category of "informed" responses, using chi-square test the AUL method had a significant positive effect on high-school biology students' NOS understanding. Similarly, the current study supports and expands the study conducted by Baram-Tsabari and Yarden (2005), the results of which indicated a positive effect of the APL method on students' understanding of scientific research. Based on the aforementioned studies, as well as on the study described herein, it is evident that the two methods afford a direct and reflective discourse regarding the various aspects of the nature of science, and contribute to students' understanding of the complexity of the NOS aspects.

The findings indicate that both the AUL and the APL methods were effective regarding the NOS aspects of the tentativeness of the scientific understanding and methodological diversity. However, only the AUL method was fully effective regarding the NOS aspects of the aims of science, the cooperative nature of the scientific process, and the sociocultural embeddedness of scientific knowledge, for which the APL method was only partially effective.

A comparison of the NOS understanding gained by participants in the two experimental groups suggests that the AUL, which involves students' visits to university laboratories, was a more effective teaching method than the APL method. This finding indicates that the reading of scientific articles as a way of teaching the topic of NOS has a more limited effect, possibly because the text does not reflect an actual research process. The direct contact with scientists in university research laboratories presents an authentic and exciting research environment that enhances NOS understanding.

The findings of the current study support those of other studies, in which the effects of reading scientific articles as a teaching method were described as limited (Medawar 1986; Woolonough 1989) and those of studies that showed the significant effect of face-to-face interaction involving an active discussion between scientists and high-school students on issues pertaining to NOS (Hodson 2012; Hodson and Wong 2014).

The current study contributes to the literature on explicit and reflective teaching of NOS as part of the *teaching as inquiry* approach. In particular, the study's findings indicate that teaching NOS using *science-as-inquiry* methods is an effective approach for teaching NOS in biology class. Thus, these results support those of previous studies regarding the science as inquiry method (e.g., Allchin et al. 2014; Eastwood et al. 2012; Faria et al. 2012; Howe and Rudge 2005; Khishfe 2014; Lederman et al. 2002; Sadler et al. 2004; Wong et al. 2008, 2011(.

At this point, it is important to note the current study's position on the ongoing debate regarding the most effective and hence preferable approach: science *as* inquiry or science *by* inquiry. First of all, the current study does not address this issue, given that this was not one of its goals. There is, however, room for future studies to use a pre-post control design in order to compare the two approaches and shed light on the issue through improved empirical evidence. Second, in terms of the high-school biology curriculum, I believe (in line with the approach of Schwab 1962), that the scientific community ought to invest efforts to implement both approaches (see for example Allchin et al. 2014), rather than leave any one of them behind. Indeed, that is the approach practiced in the context of the high-school biology curriculum in Israel. The current study's findings suggest that methods that follow the science as inquiry approach significantly contribute to students' understanding of NOS.

To summarize, the current study showed that the AUL and the APL methods are useful and can successfully be adapted for teaching various biology subjects. It remains for future studies to determine whether they are similarly effective in different cultural contexts.

Notwithstanding, it is important to note that the current study had two major limitations. First, the size of the sample was relatively small, comprising approximately 70 high-school students in each group. Second, the type of sample used was also of a limiting nature, as all of the participating schools were from the same geographic area and represent a uniform population in terms of socioeconomic status. Consequently, the results of the current study could not be generalized to populations of a lower socioeconomic status or to schools located in the country's peripheral areas. Future studies would do well to expand the size of the sample and to examine whether the effects of the two teaching methods are identical when applied with students of various socioeconomic backgrounds.

5 Challenges and Recommendations for Implementation

The main challenges common to the AUL and APL methods involve garnering the teachers' cooperation and preparing them for the different mode of instruction these approaches necessitate. The teachers participating in the study had volunteered to do so. These teachers had an average teaching experience of over 10 years and a strong research background of their own in biology. Thus, my experience in this project is based on collaboration with highly experienced biology teachers. I provided them with an intensive 2-day workshop that included lectures on the nature of science, an explanation of the rationale of the approaches under investigation, and practical experience based on modeling. The teachers read the articles, visited the research labs, and experienced the reading and analysis of the learning materials. I assume that for those with less experience or beginners in the teaching profession, who might not have a strong background in scientific research, a longer training session and more intensive preparation would be needed, to enable them to adapt these approaches successfully.

Regarding the APL in particular, the main challenge encountered involves the adaptation of articles from current scientific literature. My experience reveals that this is a highly time-consuming process that requires the cooperation of the researchers. Nonetheless, I recommend the use of up-to-date studies written by researchers at universities located close to the schools in which this method will be applied. I consider this effort to integrate a maximum level of authenticity into the learning process.

The challenges involved in implementing the AUL approach specifically involve establishing the necessary cooperation with the university and with particular researchers. Undoubtedly, such arrangements involve logistic and administrative difficulties regarding scheduling, transportation, and—above all—preparing the researchers to guide the students through their labs. In my study, a PhD candidate (in advanced stages) was selected at each lab to undergo a 3-day training session in preparation for participating in the project. This training session included two main components: (a) the elements of "successful guidance" of students and (b) the construction of the "scientific narrative." Regarding how to guide students, instruction focused on the following elements: use of level-appropriate scientific terminology, creating a flow of activities for the students that would facilitate understanding (rather than confusion), provision of clear and organized instructions throughout the visit, facilitation of the discussion, and creating stations at which students can receive guidance and can partake in the activities of the lab. Regarding the construction of the "scientific narratives," I helped the researchers to create the necessary narrative by addressing the following questions: what was known in the field before the researchers commenced their study, why this study interested them, what were the research questions, how they changed throughout the course of the study, what methods were utilized, and what was found. In addition, the researchers described the collaborations within the lab with colleagues and the head of the lab, as well as with colleagues at other labs within the university and beyond it. They reported on their conclusions, and discussed other repercussions as well. An additional challenge, as mentioned previously, is to lessen the gap between the students' levels of knowledge and familiarity with scientific language and those of the researchers. This can be addressed by applying these teaching methods after the students have studied the relevant concepts and scientific principles (as I did in the current study).

The syllabus for the two versions of the study unit that constituted the intervention included the reading of historical narratives, as well as "scientific narratives," in order to strengthen the "science as inquiry" approach. In other words, all three of the teaching methods proposed by Schwab (1962) were included in both versions of the study unit. Without detracting from the effectiveness of these methods, future studies could focus specifically on comparing the effectiveness of these and other "science as inquiry" pedagogical methods (e.g., reading of authentic scientific articles, reading adapted scientific articles, addressing socio-scientific issues, using the "invitation to enquiry" lesson format, as well as both historical and scientific narratives). This line of inquiry would further serve to address the paucity of NOS-focused research in the professional literature, as well as the need for more specially designed study materials, textbooks, and study units that implement the "science as inquiry" approach with an emphasis on reflective and explicit discourse on the aspects of NOS.

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Compliance with Ethical Standards

Conflict of Interest The author declares no conflict of interest.

Appendix 1. Abstracts of the adapted articles (translated from Hebrew to English)

Original article: *Recent shrinkage of the range of the Eastern Spadefoot Toad, Pelobates syriacus (Amphibia: Anura): archeological evidence from the Bronze Age in Israel*

Delfino Masimo, Guy Bar-Oz, & Lior Weissbrod

Published *in Zoology in the Middle East*, 40, 45–52 (2007)

Abstract for students: *Shrinkage of the geographic distribution of the Eastern Spadefoot Toad*: *archeological evidence from the Bronze Age in Israel* Following Masimo, Bar-Oz, and Weissbrod, 2007.

Archeological evidence can serve to increase our understanding of the past distribution of species that have become extinct, and it sheds light on recent changes in species variability. Such evidence constitutes complex research findings, due to its uniqueness and the fact that it cannot be replicated. Comparing the distribution of current species with that of their precursor species is needed in order to accurately assess the influence and the repercussions that climate change and human activity had on the environment, and it can help us understand the population structure of current species.

This study can be considered as an example of "basic science," because it elucidates changes in species distribution; it can also be considered an example of "applied science," because it reveals the ways in which human activity affected environmental conditions, which in turn can lead to the development of strategies for environmental preservation. Amphibians are particularly useful for conducting such a comparison, because they are considered reliable indicators of environmental conditions both on land and in water. Hence, they provide a particularly useful way to describe what local conditions were like in a specific era, as they reflect slow-paced developmental changes that occurred over many generations. Furthermore, the particular resources for which many amphibian species rely on their environment are well known, and it is assumed that their ancient precursors had the similar needs.

This article presents findings (fossils) retrieved from the archeological site, evidence of amphibian life in different eras. The analysis of the remains collected in the Ara Burial Cave in Lower Galilee, Israel (Late Bronze Age II, c. 1300–1200 BCE), permitted the identification of 725 remains of various species of *Spadefoot Toad*. Despite the relative rarity of *such* remains (attributable to a single individual), their presence in the Ara cave testifies to a wider range of the taxon in the recent past, given that in the present, this species cannot be found in the cave. *Additional evidence of the species wider dispersion in the past was* found also in several Israeli Late Pleistocene archeological sites All of this evidence suggests recent environmental changes, which may be due to climatic fluctuations as well as to human impact. An accurate analysis of the *shrinkage of the geographic distribution of the Eastern Spadefoot Toad* and of the environmental changes that led to this shrinkage will assist in the preparation of conservation or reintroduction plans in Israel.

Conclusion: Comparing the distribution of fossils with the current species distribution can serve to gain insight into the changes in environmental conditions that occurred over time and to understand the role that human activity had in causing these changes.

Original article: Effects of eight growth factors on the differentiation of cells derived from human embryonic stem cells

Maya Schuldiner, Ofra Yanuka, Joseph Itskovitz-Eldor, Douglas A. Melton, and Nissim Benvenisty

Published in PNAS, 97, 11,307–11,312 (2000).

Abstract for students: effects of eight growth factors on the differentiation of cells derived from human embryonic stem cells Following Schuldiner, Yanuka, Itskovitz-Eldor, Melton, and Benvenisty, 2000.

The process of embryo development begins with a single fertilized cell. Embryonic development occurs as cells divide; thus, the number of cells increases, and tissue and organs form through cell differentiation. Embryonic stem cells are harvested from embryos in very early stages of development and then are placed in a cell culture, where they can grow in vitro, that is, outside of the living organism, in the laboratory, under carefully monitored conditions.

Stem cells are characterized by two major traits:

1. The ability to constantly self-multiply in a cell culture
2. The ability to differentiate (become a mature cell with a specific role and thus different from the parent cell) into every type of cell in the human body, for example, blood cells, muscle cells, nerve cells, etc.

Cell differentiation leads to changes in cell morphology (structure) and function. In the differentiation process, specific genes are expressed that are characteristic of specific cell types, for example, genes of white blood cells or genes of antibodies.

When embryonic stem cells are grown in a cell culture under specific conditions (appropriate temperature and salinity, among other factors), cell clusters are formed, which after a few days become small droplet-shaped bodies that are called *embryoid bodies*. To use stem cells for purposes of basic science or applied science (for example, for medical research), scientists need to develop techniques by which to direct cell differentiation towards a particular function. One of the ways to try to accomplish this is by growing the cells in a solution that contains special proteins that influence the development and growth of the cells. These proteins are called *growth factors*, and different growth factors naturally induce cell differentiation into different types of cells.

This article describes a study that aimed to review the distinct effects of eight different growth factors on stem cell differentiation, to determine whether it is possible to control the cell differentiation and thus direct stem cells to differentiate into specific cell types.

The findings show that human embryonic stem cells that developed from embryoid bodies expressed a receptor for each of these growth factors, and that their different effects were evident by differentiation into cells with different morphologies. However, none of the growth factors directed differentiation exclusively to one cell type. By analyzing the resulting cell morphology, we were able to detect three categories of morphological differences associated with three groups of growth factors. This analysis is an initial step towards demonstrating that it is possible to use specific factors to direct the differentiation of human embryonic stem cells in vitro.

Appendix 2

Table 6 Examples of students' quotes

Aspects of NOS	Inadequate	Adequate	Informed
Tentativeness	Modern scientific knowledge is knowledge with more information than in previous years.	Modern knowledge is based on knowledge from previous years. In some cases the former refutes the latter.	Scientific knowledge constantly develops and changes. For this reason there will always be different explanations. Despite the fact that they will not necessarily be "better," they will be more relevant and inclusive. There will always be new things that science cannot explain. The more things are explained, the more new, unexplainable things are revealed.
Cooperative nature of the science	Most researchers prefer to work alone, without cooperating with other researchers—thus they can claim all the credit for themselves.	Cooperation between researchers will produce nice results. Independent research does not significantly advance science.	Information sharing is important to advance research and is therefore an integral part of research. Without consulting, learning and discussion with other researchers, there will be no development of science. By working cooperatively, more precise and more objective results can be attained, and the study's reliability is maintained. In science, all research is based on prior studies and the work of other

Table 6 (continued)

Aspects of NOS	Inadequate	Adequate	Informed
			researchers; no one can conduct research in an intellectual vacuum. Scientists publish articles, attend conferences, in order to cooperate and help science and humanity advance.
Methodological diversity	There is one basic research method that characterizes any scientific research—research question, hypothesis, experiment with a control group, results, and conclusions.	The methods are different because the areas being researched are different.	Research in different fields uses different investigative methods. For example, each field investigates different types of objects, and conducts the research in different locations and settings. In the case of cell biology, there is the matter of controls, replications, more work in the lab. With ecology, there is more observational research in the field, the choice of a reasonable hypothesis from all of the possible hypotheses.
Sociocultural embeddedness	Scientists conducting scientific research are only influenced by science, because only science influences the researchers. Scientists remain uninfluenced, because science negates religion, and society cannot influence existing facts.	There are scientists who will not perform certain experiments because it goes against their religion. A religious researcher will hold different beliefs about evolution, creation, and other issues than those held by a non-religious scientist, or those held by a scientist from a different religion.	Scientists are also citizens of a country and therefore the government has the right to oversee their experiments. For example, in the US scientists cannot engage in research using stem cells, because the government does not permit it. In addition, scientists are also people and people are certainly influenced by the society in which they live.
Aims of science	If the research does not help anything, there is no point in wasting resources and energy on it. Most research projects must help humans.	Research projects should be done to enrich our knowledge and not only for practical needs.	It is also important to conduct research projects that do not lead to any practical developments, because they can explain phenomena, present new knowledge or knowledge that had been missing, or it could provide new information that alters a currently accepted theory. In addition, theoretical research can have practical implications in the future.

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