

Open Inquiry based learning experiences to understand the Nature of Science

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Abstract

In this paper we address the question of the efficacy of an inquiry-based learning approach, with different levels of teacher's guidance, to introduce the students to fundamental aspects of the Nature of Science (NoS). Explicit pedagogical approaches, in which specific instruction on the topic of NoS is provided in addition to the engagement in scientific inquiry, are generally considered more effective with respect to implicit methods, where NoS conceptions are expected to develop as a natural consequence of inquiry-based learning experiences alone. In our study, we further explore the connections between scientific inquiry and implicit development of NoS conceptions, by investigating the efficacy of different kinds of inquiry approaches. Our findings confirm limited gains in developing NoS views by following a guided inquiry approach and suggest a more efficient NoS instruction by applying integrated open-inquiry-based teaching strategies.

Keywords: Open Inquiry, Integrated Teaching Strategies, Nature of Science

Introduction

Much of the interest in science and engineering education today is focused on achieving adaptive expertise (Redish & Smith, 2008), in terms of developing both specialist-discipline knowledge, abilities to solve practical problems, creativity in the design process, competences on using mathematical, scientific and technological tools to analyze and interpret data (Rocard et al., 2007; NRC, 2011). An effective science instruction should provide the students with a deeper understanding of disciplinary concepts and, at the same time, fundamental epistemological resources able to strengthen their reasoning skills and transversal abilities (NRC, 2012). In this view, an inquiry-based approach (Llewellyn, 2002) to teach science in K-12 levels of instruction is currently considered the most natural viable solution for promoting the development of all these competencies.

In inquiry-based learning environments, the students are engaged in identifying scientifically oriented questions, planning investigations, collecting data and evidences in laboratory and/or real life situations, building descriptions and explanation models, sharing their findings and eventually addressing new questions that arise. These activities are the same that real scientists carry out when perform their investigations. For this reason, these are considered the most effective way for developing scientific knowledge and stimulate the strengthening of logical and reasoning abilities. However, depending on the amount of support provided by the teachers, the students may be involved in more or less guided inquiry (GI) or open inquiry (OI) (Banchi & Bell, 2008). At this regard, the role played by the teacher is fundamental for the achievement of the desired results. In fact, it seems that a more guided instruction should provide the students with competencies more focused on conceptual knowledge, leaving the learners with a not well defined view of how scientific knowledge is produced (Chinn & Malhotra, 2002). On the other hand, a more open approach would let the students to experience a learning path with a higher level of

autonomy on deriving the inquiry questions, designing procedures and experiments, analyzing data and drawing their own conclusions. The OI-based learning, however, requires higher-order thinking skills that rarely can be found in younger students, which may develop feelings of frustration due to the lack of achieving the desired goals independently from teacher's hints (Quintana, Zhang, & Krajcik, 2005). In fact, results reported in literature are not ubiquitous for what concerns the efficacy of the IO-based method to produce an effective conceptual knowledge, while a more cohesive view supports this approach as the most suitable way to develop a deeper understanding of the NoS (Schwartz, Lederman, Crawford, 2004; Capps & Crawford, 2013).

Within this educational framework, we present in this paper the preliminary results from an extended study regarding the relationship between inquiry based instruction and the development of NoS conceptions. Here, we first introduce the theoretical framework which shaped the design and development of this work. Secondly, we report the outcomes, concerning NoS aspects, from a questionnaire that was administered to a sample of secondary school students who experienced a GI-based instruction within the context of ESTABLISH, a FP7 European Project aimed at promoting inquiry-based strategies for teaching science in European secondary schools. Then, we report the results obtained from the analysis of an OI-based learning path experienced by a sample of young engineering students at the Physics Department of the University of Palermo, Italy. A final discussion about our findings and concluding remarks are provided in the last part of the paper.

Inquiry-based instruction and Epistemology of Science

In inquiry based instruction, the amount of information and support provided by the teachers may affect the learning efficacy on specific conceptual and/or epistemological targets. Usually, in GI the teacher provides the students with the research questions, and the students design the procedures to find reasonable answers and/or test the resulting explanations. In OI-based instruction, the teacher takes the delicate role of defining the context for inquiry, stimulating the students to derive their own questions, design and carry out independent investigations, construct coherent explanations, share their findings. This teaching strategy should be helpful to develop higher skills of scientific thinking, but, at the same time, it requires the students to face great reasoning efforts. Moreover, the way the inquiry process itself is driven within the class has direct consequences upon the epistemological ideas that students might bring to bear on their work and on how the learning activity may change their perspective on scientific knowledge (Sandoval, 2005; Oliveira et al., 2012).

In the last decade, several studies have addressed the question of the efficacy of an OI methodology on teaching science concepts and/or developing NoS views, in comparison with traditional instruction or GI-based teaching approaches. Berg et al. (2003) report a better conceptual understanding in students carrying out the same experimental activity by following an OI-based laboratory with respect to those following an expository-structured learning path. An in-depth comparison between GI and OI learning approaches was presented by Sadeh & Zion (2009), who compared the mean scores achieved by two groups of 12th grade students. In their study, the OI group outperformed the GI one only in aspects concerning the perspectives of critical and reflective thinking about the process.

Recent studies suggest that a physics instruction based on GI, without providing an explicit attention to NoS aspects, seems to be more effective on repairing students' misconceptions (Nottis, Prince, & Vigeant, 2010), with respect to produce useful epistemological perceptions of science (Bell et al., 2003). On the other hand, students involved in OI

learning experiences, having the purest opportunity to act like scientists, would gain a deeper view of the nature of science and the awareness of the process of scientific inquiry (Capps & Crawford, 2013). Unfortunately, this latter approach, requiring the greatest cognitive demand from students in terms of scientific reasoning, may induce feelings of inadequacy or frustration, due, for example, to achieving of undesirable results, and could not bring about an effective understanding of the concepts (Millar, 2012). In summary, it seems that both approaches, individually considered, could not result effective enough, suggesting to take into account integrated teaching/learning strategies.

Many researchers have become increasingly interested in the interplay between science conceptual learning and other cognitive factors, such as personal learning frameworks (Hogan, 1999), learning beliefs, and science epistemologies (Hammer, 2002). It has been shown that students' epistemological beliefs about science play a significant role on their ability to solve physics problems (Bing & Redish, 2009, Kuo et al., 2013).

From an epistemological perspective: *Inquiry is the process of doing science*. There are two main reasons why an understanding of scientific epistemology needs to be included as a fundamental aspect within inquiry-based science education:

- i. The understanding of epistemological frames, characterizing the inquiry approach, will help the students to gain the awareness of their cognitive processes, causing an improvement of their learning performances.
- ii. The development of sophisticated epistemologies of science would provide powerful tools for thinking to citizens in their everyday lives.

In order to design an effective inquiry-based instruction, it is not sufficient to know what students know about a topic. One must consider the opportunity to produce a fruitful change on students' epistemologies of science, which are not globally robust beliefs that drives students' learning and problem-solving, but rather context-dependent locally-coherent views whose stability depends both on external inputs and on students' internal conceptions and emotional states (Gupta & Elby, 2011). At this regard, a very recent study support the efficacy of an *implicit* method of NoS instruction for students enrolled in classes using the *Physics by Inquiry* curriculum (Lindsey et al., 2012).

Our guiding idea is that OI-based teaching strategies, promoting an involvement in activities similar to those carried out by scientists, should provide the students with the opportunity to deepen their understanding on how scientific knowledge is produced in real research contexts. In addition, the engagement of the students within highly motivated inquiry-based learning environments should avoid the development of negative affective components.

The ESTABLISH Project and the NoS

ESTABLISH (European Science and Technology in Action: Building Links with Industry, Schools and Home) is a four year (2010-2013) project funded by the European Commission's Framework 7 Programme for Science in Society, aimed at promoting and developing the Inquiry-Based Science Education (IBSE) in European secondary schools. The ESTABLISH group consists of over 60 partners from 11 European countries, working with science teachers and educators, the scientific and industrial communities, the policy makers responsible for science curriculum and the science education research community. The project has informed the development of teaching and learning materials aimed to provide both in-service and pre-service teachers with appropriate educational supports for

a professional development, suitable designed to promote the use of IBSE in high school classrooms across Europe.

The Italian team of ESTABLISH has contributed to the project by providing many different contributions. One of these regards the preparation an articulated GI-based learning unit on thermal science, which was first experienced by a selected group of in-service teachers, in terms of a pilot validation, and then administrated to a wide sample of secondary school students.

Our sample consisted of 55 students, selected from three different high schools in Sicily, aged between 15 and 19 and with no previous experience in inquiry based learning. The feedback from our students before and after this learning unit was collected by using the pre-post activity Establish-2A questionnaire, explicitly designed to collect opinions about learning and understanding science in students from upper secondary schools. Within this questionnaire, five aspects of NoS were addressed and specifically investigated in our work (see Table 1).

Table 1. Results from the ESTABLISH project.

NoS-related concepts	Percentage of agreement	
	Before	After
Science can be learnt only by studying textbooks, avoiding to follow own experiences	73%	64%
Remembering facts is very important to understand science	86%	72%
To understand science, the formulas are really the main thing	77%	61%
In science, the facts speak for themselves and cannot support multiple theories	55%	52%
A theory explaining experimental results cannot change	88%	73%

The Establish-2A questionnaire focuses on those aspects of NoS which are the most commonly observed in students' discussions about science. The fact of considering the textbook as a sacred oracle of absolute truths (the formulas), independently from personal experiences, or a theory as an unchangeable piece of knowledge, or the importance of remembering facts, can be considered as real cognitive obstacles to the learning process. The percentages of agreement to a given NoS concept reported in Table 1 represent the percentages of students who agreed with the idea exposed in that specific statement, respectively before and after experiencing the inquiry-based learning path. Our pre-activity results show very high percentages, as expected in learners who have never been involved in the practice of science. Post-activity percentages are all lower than those recorded before the beginning of the project. However, we may argue that our students, engaged in GI-based experiences and without any specific instruction on NoS, do not significantly change their views.

The Mission to Mars project: an OI-based learning experience

Generally, physics instruction of engineering undergraduates is more oriented towards a functional approach of scientific knowledge. Students are often trained to solve physics problems automatically by simply applying mathematical tools, and it might seem that they actually do not need to hold a NoS view. However, the development of NoS conceptions in engineering students should be strongly encouraged by the benefits they may receive, in terms of strengthening of reasoning abilities and advantages on developing a scientific thinking.

We have investigated the efficacy of an OI-based learning environment to implicitly develop NoS conceptions in university students who already attended a curricular physics instruction. A sample of 30 engineering undergraduates was involved in a challenging learning environment, starting from the problem of projecting a thermodynamically efficient space base on Mars, and performed a 6-week long research-like experiences regarding the topic of thermal energy exchange by conduction, convection and radiation.

The project was developed by following the 5E model (Bybee, 1993) of sequencing learning experiences that leads students through five phases of learning:

- **Engagement:** the educators presented the project to the students, providing a brief description of the context in which their work would have been developed and the motivation for an active participation. Students were asked to work in groups and to perform scientific investigations devoted to the design, realization and testing of smart devices, having physical characteristics able to maximize the capture and storage of thermal energy from the Sun and/or systems with high insulating efficiency.
- **Exploration:** Students dedicated the second phase of the project to acquire information and plan their activities. In this phase, the students were introduced to our laboratory and stimulated to explore the measurement facilities and available materials in order to design their own experiences.
- **Explanation:** Students carried out their research investigations, designed on the base of their hypotheses pointed out during the explorative phase. They dedicated about thirty hours to complete their laboratory activities by collecting, processing and analyzing data.
- **Elaboration:** Students shared their ideas and preliminary results with the other participants and finally presented the most significant findings via oral presentations and by writing a final scientific report.
- **Evaluation:** A final phase has been devoted to a classroom discussion aimed at comparing and contrasting the results obtained by different groups of students.

Students spent a total amount of about forty hours to plan and realize a complete scientific research, concerning the design and practical realizations of smart devices, in the context of a hypothetical project about the construction of a thermodynamically efficient space base on Mars. The choice made by the educators to drive the students' inquiry within the context of a space science challenge strongly motivated the students, who, of course, were conscious that their research work was not part of a real space project, but they participated to the activities with equally high emotional involvement, being convinced of the importance of actively participate to a real research experience.

The results of this study are based on the analysis of the students' questionnaires, planning files, logbooks of experiments, final scientific reports. The data were analyzed on the basis of an in-context search for key-words or phrases and specific aspects of the students' answers that could give evidence of the cognitive process. In Table 2 we report the list of

five NoS aspects on which the literature generally agrees to consider them as the basic characteristics of the scientific knowledge. We have carefully examined both written and video recorded students' productions and reported the percentage of students mentioning NoS aspects during the project phases.

The percentages of students mentioning specific aspects of NoS show a general trend that increases through the phases of the project. This represents a global positive result, even considering the intrinsic differences between the initial explorative phase of the project, the intermediate parts, strictly devoted to practical experimentations and the search for explanations and the final one reflecting the great reasoning efforts. In particular, we find that few students considered the tentative aspect of the scientific knowledge at the beginning of the project, during the engagement phase, while almost half of them is already convinced that science is based on empirical basis.

Table 2. Results from the "Mission to Mars" project

NoS aspects	Percentage of students mentioning NoS aspects during the project phases				
	Engage	Explore	Explain	Elaborate	Evaluate
Scientific knowledge is:					
1) Tentative	17%	37%	33%	40%	53%
2) Grounded on empirical basis	47%	63%	77%	67%	73%
3) Based upon observations and inferences	40%	57%	77%	73%	80%
4) Creative	30%	47%	57%	63%	63%
5) Theories and laws are different forms of scientific knowledge	13%	27%	47%	57%	67%

Before this OI research-like experience only few students knew that theories and laws are different forms of scientific knowledge. Most students seem to believe that scientific knowledge is certain and this contrasts with its tentative nature, but our results show that during this project more than half of the students developed the understanding of the tentative aspect of the NoS. Higher percentages are found on all the other four peculiarities of the scientific knowledge. As expected, this practical experience within the context of a research project strongly reinforced the students' conception of a scientific knowledge grounded on experiments. Students usually think that scientific knowledge resides directly in experimental results, but here they learned the importance of reasoning (inferences) about the significance of their findings. Students initially believed that theories and laws were related in a linear hierarchy, but at the end 67% of them learned that theories and laws are different forms of scientific knowledge. After this experience, many students consider creativity as playing a major role in science construction.

Conclusions and future prospective

The development of scientific epistemology is an explicit goal of recent educational reforms, mainly driven by the conception that students' ideas about NoS influence their efforts to conduct (and learn) science. Of course, students need to understand disciplinary concepts and inquiry-based instruction is intended to help students' learning. Disciplinary scaffolds grounded within epistemic structures might guide students' inquiry and help them to see how to use disciplinary concepts to explain particular events. The use of integrated conceptual and epistemic guidance favors the activation of cognitive resources useful to articulate explanations.

In this work, preliminary results from questionnaire outcomes administered to secondary school students within the ESTABLISH project have shown modest benefits from a GI-based instruction in terms of an understanding about NoS aspects implicitly addressed. This result could be due to a lack of reasoning efforts in students, who are guided by the teachers step-by-step across the inquiry-based learning phases.

On the other hand, an OI-based learning environment has been experienced by a sample of engineering undergraduates who already attended university-level courses on physics concepts. Despite their previous instruction, students showed very low initial outcomes concerning the main aspects of NoS (see the percentage on the engage phase reported in Table 2). However, we have found that a highly motivating research-based environment, stimulating autonomous reasoning and problem solving abilities, may constitute an efficient teaching/learning approach both to consolidate tough physics concepts and, at the same time, to clarify important aspects of NoS. We believe that an IO-based approach could be effectively applied to implicitly teach NoS aspects to students who already have a solid background of conceptual knowledge. In these terms, the integration of curricular instruction with teaching/learning strategies based on OI approaches seems a viable solution to achieve useful NoS conceptions.

We finally point up that the two inquiry-based teaching-learning experiences here described and analyzed were deeply different for both the level of guidance provided by instructors to the learners and the different target of student population. A direct comparison between the two teaching approaches (GI and OI), although interesting and useful, is beyond the aim of this paper and it could be the subject of future investigations.

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