Sci & Educ (2018) 27:435–455
https://doi.org/10.1007/s11191-018-9984-9

ARTICLE

The Nature of Scientific Practice and Science Education

Rationale of a Set of Essential Pedagogical Principles

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Abstract There is, broadly speaking, an agreement within the international science education community that comprehension of the nature of science (NOS) should be a key element in the scientific literacy of citizens. During the last few decades, several didactic approaches have emerged concerning what and how to teach NOS. Also, one of the basic objectives of science education is for students to become familiar with the skills typical of scientific practice; however, there is little reference to their need to also acquire meta-knowledge about scientific practice (i.e., an understanding of the nature of scientific practice). Among other reasons, this may be due to NOS being essentially identified in most of the predominant proposals with the nature of scientific knowledge. But why not plan the teaching of science to be in tune with real scientific practice for students to learn about the nature of scientific practice at the same time as they are learning science? The answer to this question has given rise to a proposal grounded in ten essential pedagogical principles for the teaching and learning of science in secondary school. These are the principle of formulating questions, the principle of creativity and imagination, the principle of experimentation, the principle of procedural diversity, the principle of errors as opportunity, the principle of modeling, the principle of cooperation and teamwork, the principle of argumentation and discussion, the principle of communication, and the principle of evaluation. The purpose of this article is to present the justification and fundaments of these principles.

Keywords Science education · Nature of science · Nature of scientific practice · Pedagogical principles

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1 Introduction

For some years now, the international science education community has been demanding that understanding the nature of science (NOS) be an essential component of citizens' scientific literacy (Acevedo and García-Carmona 2016; Hodson 2014; Organization for Economic Co-operation and Development [OECD] 2016; Next Generation Science Standards [NGSS] 2013). The reasons for this are many, although perhaps the most noteworthy is that such an understanding, more or less well informed, is what people tend to make use of when they are evaluating public issues related to science and technology (Shamos 1995). And, undoubtedly, a good understanding of NOS together with a training in how to apply this in the analysis of scientific and socio-scientific issues will help those evaluations be more critical, responsible, and constructive (Acevedo-Díaz and García-Carmona 2017). This idea is in accordance with one of the fundamental objectives of the educational project IRRESISTIBLE (*Including Responsible Research and innovation in cutting Edge Science and Inquiry-based Science education to improve Teacher's Ability of Bridging Learning Environments*), which is funded by the European Union within the *Science in Society* programme (Laherto et al. 2018).

However, education research reveals that neither learners nor teachers of science usually have a sufficiently informed understanding of NOS (García-Carmona et al. 2011, 2012; Lederman 2007). Realistic education proposals with relatively modest objectives are necessary to favor the teaching of NOS notions in class (Matthews 2012), as also are empirical studies to analyze their educational effectiveness with rigor (Acevedo-Díaz et al. 2017a).

Educational administrations and/or science educators in some countries such as Brazil, China, Taiwan, the USA, and Turkey are giving notable, explicit attention to the understanding NOS. However, in most other countries, not only does there still is a long way to go, but also there has hardly even been a start made. In Spain for example, in addition to the sparse incidence of NOS in science classes (Acevedo and García-Carmona 2016; Banet 2010), there are minimal explicit allusions to it in the current official curricula of school science, a situation which can clearly be improved (Acevedo-Díaz et al. 2017a). The only proposals are of standards of learning related to the development of competencies for scientific practice, but no demand is made for a meta-cognitive understanding of scientific practice which is what, among other aspects, NOS refers to. In addition, the official curriculum favors the transmission of certain inadequate ideas about science. As an example, a curriculum item is "The scientific method: Its stages" as if there were a universal and algorithmic scientific method. Therefore, much more education research is still needed for its results to be transferred to official curricular requirements, science teacher training, and, ultimately, the classes themselves. In addition, even science teachers with an adequate understanding of NOS usually do not include it among the basic objectives of their teaching plans (Akerson and Abd-El-Khalick 2003).

All this leads one to wonder whether attention to NOS should be the central underlying theme in science education, going beyond the objectives set for learning to also permeate everyday work in science classes. From the international bibliography, it is clear that there is a broad consensus that the most effective way to learn about NOS is through explicit and reflective education approaches (Abd-El-Khalick 2012; Acevedo 2009; Lederman 2007; Clough 2011), through establishing specific learning objectives, and through designing activities focused on the students' critical thinking and discussion about aspects of NOS. There is also evidence that learning about NOS is favored if it is promoted in a contextualized way. This may be through the analysis of narratives about the history of science (Acevedo-Díaz et al. 2017a; García-Carmona and Acevedo 2017; Irwin 2000; Rudge et al. 2014), the analysis of contemporary scientific and socio-scientific problems (Eastwood et al. 2012; García-Carmona and Acevedo 2016), or as part of real scientific inquiries (Schwartz and Crawford 2006) if these are accompanied by tasks for meta-cognitive reflection on the procedures that have been followed (García-Carmona 2012a).[1] In addition, the integration of NOS with other content of the school science curriculum has the advantage that it can favor the learning of that other content (Michel and Neumann 2016) and thus encourage teachers to incorporate it into their already established teaching plans (Bell et al. 2012).

But, how can basic meta-knowledge about what scientists do while they are constructing knowledge, inspire pedagogical principles for science teaching, and be congruent with and help to understand real scientific practice? The underlying hypothesis is that if you work in class in a similar way to scientists and reflect explicitly upon it, then students' meta-cognitive understanding of scientific practice may be improved, and their learning of science favored. This approach must be projected, logically, within the limits and particularities of the area of education (Reif and Larkin 1991). It fixes the focus on the student as well as the teacher. The elaboration of science teaching plans in tune with real scientific practice requires a prior meta-cognitive reflection on the part of the teacher.

The metaphor of the student as a scientist was already discussed during the last decades of the twentieth century in the context of constructivism-based approaches to teaching (Gil 1994). This perspective, however, in addition to the focus mainly on learning science rather than learning about science, was based on the psychology of learning (Pozo and Gómez Crespo 1998). It gave rise to teaching models based on students' alternative conceptions, conceptual change, and learning through inquiry (Marín 2003). The strengths and weaknesses of these models have been widely discussed in the science education literature (Duit and Tragust 2003; Gilbert and Watts 1983; Rönnebeck et al. 2016).

One may therefore state that a didactic approach to science teaching, guided by meta-knowledge about scientific practice, is an educational innovation that as yet has hardly been studied at all. Indeed, we only know of some approaches focusing on learning science through inquiry (Abd-El-Khalick 2013; Domin 2009). Thus, the purpose of the present article is to present a grounded proposal of some essential pedagogical principles for science teaching in secondary school (12–18 years old), so as to contribute to the improvement of science teachers' pedagogical content knowledge for their teaching of NOS, and therefore to their students' understanding of the nature of scientific practice.

2 Nature of Science in Science Education

One could define NOS as the meta-knowledge about science which emerges from interdisciplinary reflections made from the perspectives of the philosophy, history, and sociology of science, as well as from those of scientists and science teachers. But, what is science? The answer is not straightforward, and any attempt to give a simple definition may lead to limited or distorted views. In general, it can be said that science is a field of human knowledge aimed at understanding the natural world, which consists of (Bell 2009) (i) a body of knowledge (facts, definitions, concepts, models, laws, theories, etc.), (ii) a way of knowing (creative, accepting

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[1] In accordance with the research done so far on understanding NOS, it is naive to think that students will learn about NOS by merely handling basic science procedures in class (there is actually evidence that this does not work by Bell, Abd-El-Khalick and others, where they compare explicit and implicit methods).

controversy, cooperative, and collaborative, based on empirical tests, intersubjective, tentative, etc.), and (iii) a set of processes (observation, measurement, classification, modeling, inference, theorization, etc.). In addition, (iv) its development is influenced by the technology, culture, economics, politics, etc. that are dominant in each era, and vice versa (Acevedo and García-Carmona 2016).

In the international panorama, the proposal of Lederman and co-workers (Lederman 2007; Lederman et al. 2002) concerning which contents of NOS to address in science teaching has dominated. This proposal is characterized by a focus towards the epistemic aspects of science, i.e., its cognitive or rational aspects. It basically refers to the nature of the scientific knowledge that is produced (Lederman and Lederman 2012; Lederman et al. 2014a), i.e., the proposal of content concerning NOS is essentially delimited to the nature of the “final product of scientific research.” Understanding of scientific inquiry, which is what one might identify with knowledge about scientific practice, is thus left out of NOS to be analyzed separately (Lederman et al. 2014b). Nonetheless, prior to Lederman and co-workers’ proposal, Driver et al. (1996) argued for considering scientific processes and methods to be part of the epistemological knowledge of NOS. This position has also been defended by other authors (Acevedo and García-Carmona 2016; Matthews 2017).

As mentioned above, however, teaching proposals about NOS have paid scant attention to the non-epistemic aspects of NOS, i.e., to the contextual, social, and psychological aspects related to science and scientists. There have only been minimal and very generic allusions made to these in contrast with the epistemic aspects. Some examples of these allusions, however, are that there are social and cultural influences affecting scientific knowledge (Lederman et al. 2002), that science is part of social tradition, and scientific ideas are affected by their context (McComas and Olson 1998), and the importance of cooperation and collaboration in the development of scientific knowledge (Osborne et al. 2003). But, science historians, philosophers, and sociologists have indeed highlighted the strikingly clear influence of non-epistemic aspects in the development of science (Acevedo 2006b; Forato et al. 2011; Matthews 2012). Science is a creative activity that responds to (and is subject to) social, economic, political, and cultural problems, needs, and interests (Acevedo 2006a). Therefore, teaching NOS should also take into account all these aspects at the same level as the epistemic factors in order to improve citizens’ scientific culture (Acevedo-Díaz and García-Carmona 2017).

Recently, the consideration of non-epistemic aspects in order to provide a more holistic view of NOS has been gaining support. Abd-El-Khalick (2012) added the social dimension of science to his original proposal in a somewhat more developed way, indicating that scientific knowledge is developed collectively, scientific institutions are governed by identifiable norms, and the objectivity of science is achieved through processes of intersubjectivity within the scientific community. Acevedo and García-Carmona (2016) included two dimensions from the sociology of science: (i) internal (social construction of scientific knowledge, scientists’ interests and values, communication of the results of scientific research, interactions among scientists, etc.), and (ii) external (influence of science on society and vice versa, social problems and decision-making, social responsibility, influence of politics, religion and lobbies, financing, etc.). Irzik and Nola (2014) suggested considering a social and institutional dimension of science (professional activities, certification and dissemination of scientific knowledge, scientific behavior, social values, etc.). Dagher and Erduran (2016) extended this dimension with allusions to social organizations and interactions, public power structures, and science funding. Martins (2015) proposed a historical and sociological axis for teaching NOS, which includes the role of scientists and the scientific community, intersubjectivity, scientific communication, moral, ethical, and political scientific issues, as well as social and historical influences.

In view of the above, the position that the present work adopts on teaching NOS content is that proposed by Acevedo-Díaz et al. (2017a).[2] This integrates, in similar proportions, epistemic and non-epistemic aspects that emanate from an exhaustive review of the literature on the philosophy, sociology, and history of science, as well as that on science education related to NOS. The content of this proposal is summarized in Table 1. It is necessary to say that the feasibility of this proposal with both secondary education students and pre-service secondary science teachers has been verified in a recent research project conducted by these authors (Acevedo-Díaz et al 2017a).

2.1 Nature of Scientific Practice

In accordance with what was stated above about the conception of science, it can be said that scientific practice would integrate aspects related to the way of knowing and the set of processes followed by scientists in their research. Consequently, meta-knowledge about the issue would constitute what is known as the nature of scientific practice, which itself constitutes a subset of NOS. In Table 1, the nature of scientific practice comprises epistemic and non-epistemic aspects of NOS, specifically, aspects corresponding to the dimensions "Nature of the processes of science" and "Factors internal to the scientific community."

Although all the aspects integrating the two dimensions are important, it would be very extensive, as well as counterproductive educationally, to develop each and every one of them here. If the intention is to take advantage of what is provided by knowledge about the nature of scientific practice so as to then establish pedagogical principles that can help students learn about it, then the ideal will be to prioritize those aspects that (1) are relatively easy to implement, taking into account the usual reality of a science classroom of secondary school (the results of education research would help with this); (2) promote working strategies and dynamics in class (it would be more suggestive, for instance, to pay attention to the role of questions for initiating an inquiry than to focus on the professional relationships among scientists); and (3) are coherent with the values of education (for example, it would be much more interesting to address cooperation rather than competitiveness among scientists).

In accordance with all this, the aspects selected for the elaboration of the aforementioned pedagogical principles are developed briefly below, some of them imbricated within the same single explanatory context:

- *Role of research questions* (Chin and Osborne 2008; Gale 1978; Harlen 2013; Lederman et al. 2014a, b; Vale 2013). Scientific research always starts with questions. These questions are characterized by being investigable, i.e., they encourage the formulation of scientific hypotheses and the design of experiments (mental and/or empirical), models, etc., for their verification. Research questions are not always aimed at checking a hypothesis (exploratory studies are an example). The processes of an investigation are always guided by the question posed.

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[2] The authors only presented the relationship of aspects of NOS they had implemented and evaluated within the framework of an educational research project about understanding NOS using the history of science. Obviously, more aspects could have been included, such as the role of mathematization in science, æsthetics in science, science and art, etc.

Table 1 A proposal of epistemic and non-epistemic content to teach NOS (taken from Acevedo-Díaz et al. 2017a)

Epistemic aspects of NOS	
Nature of scientific process	Nature of scientific knowledge
• Observation and inference	• Characteristics of a scientific theory
• The methodology of science	• Differences between scientific laws and theories
• Role of hypotheses	• Differences and relationships between science and technology
• Creativity and imagination	• Differences in scientific interpretations of the same phenomenon
• Role of experimentation in science	• Tentativeness of scientific theories
• Role of errors in the development of science	• Dominance of some scientific theories over others
• Influence of scientists' beliefs, attitudes, and skills	• Tentative and dynamic nature of scientific knowledge
• Role of classification schemes	
• Interest of scientific controversies for the advancement of science	
• Research designs and experimental results	
• Influence of scientists' specialisms in their planning and development of scientific research	
• Role of research questions	
• Models and modeling in science	
Non-epistemic aspects of NOS	
Factors internal to the scientific community	Factors external to the scientific community
• Role of scientific communication	• Political influences in science
• Professional relationships in the scientific community	• Role of patents
• Scientists' personality	• Historical, social, and cultural context
• Personal relationships among scientists	• Influence of nationalist patriotism
• Role of scientific community in the acceptance of scientific theories	• Political support for scientific research
• Rhetorical skills and semantic strategies to persuade through own ideas	• Economic support for scientific research
• Scientific collaboration and cooperation	• Influence of society on science
• Scientific competitiveness	• Influence of science on society
• Moral and ethical issues	• Impact of science on socioeconomic issues
• Gender influence	• Science and religion
	• Role of the media in science dissemination

- *Importance of creativity and imagination* (Hull 1959; Lederman et al. 2002; Osborne et al. 2003; Weinberg 2015). Scientists have to be imaginative to be able to formulate their research questions, establish explanatory hypotheses, develop models, design the best experiments to advance their research, detect errors and anomalies, and even realize that these could lead to new discoveries.
- *Role of experimentation in science* (Asikainen and Hirvonen 2014; Hodson 1988; Hull 1959; Lunetta et al. 2007; Weinberg 2015). Some concepts or scientific ideas are theoretical and arise from logical reasoning, but whenever possible, they should be tested in experiments for their validation.[3] The result of a single experiment is not enough for new

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[3] It should be noted in this regard that not all sciences are experimental disciplines in a strict sense. For example, it is not possible to make direct experimental manipulations with phenomena in Astronomy or Earth Sciences (Acevedo 2018; Irzik and Nola 2011).

scientific knowledge to be accepted. Thought experiments are also especially interesting in the development of science, above all in hypothesis formulation and modeling.

- *Scientific methods* (Hein 1961; Hempel 1966; Hull 1959; Kuhn 1962; Lakatos 1978; McComas 1998). Scientists use a diversity of approaches and strategies to generate knowledge, including observations, modeling, data collection, inferences, experimentation, etc. These approaches and strategies are influenced by the scientists' theoretical reference frame, as well as by their beliefs, attitudes, skills, and creativity. The different classification schemes also influence the methods because they guide the research in one way or another. Therefore, there is no algorithmic, unique, and universal scientific method. Sometimes casual or unexpected (serendipity) findings also occur which are important for science.
- *The role of errors in the development of science* (Allchin 2004, 2012; Weinberg 2015). Errors are frequent and unavoidable in scientific research. An error is usually the rule rather than the exception. However, it is one way that science advances. Some errors may delay the progress of science, but others may lead to new discoveries. When scientists learn from their errors and correct them, science progresses. Also, in the development of new theories, scientists need to make assumptions about the behavior of nature. These assumptions do not necessarily have to be true for science to advance. On many occasions, great discoveries have been made by refuting a theory and learning from its false assumptions.
- *Models and modeling in science* (Acevedo-Díaz et al. 2017b; Adúriz-Bravo and Ariza 2014; Giere 2004; Justi 2006; Morrison and Morgan 1999; Oh and Oh 2011). Models constitute one of the main instruments of science. They mediate between scientific theories and physical reality. Models are used by scientists to represent, explain, and predict natural phenomena, as well as to think about and communicate scientific ideas. Although they do not fit perfectly into all the details of the phenomenon studied, models can provide useful information about the phenomenon's characteristics and functioning. Scientists spend a lot of time constructing, testing, comparing, and evaluating models (modeling). Currently, there is a preference for studying and understanding scientific theories from their models (semantic vision) instead of from their associated scientific laws (syntactic vision).
- *Scientific collaboration and cooperation* (Abd-El-Khalick 2012; McComas 1998; Osborne et al. 2003). The idea of the solitary scientist is a myth, especially in modern science. It is difficult to find a recent scientific discovery attributable to an individual scientist. Scientific advance is achieved thanks to the work of many scientists working in a coordinated and cooperative way in teams, communities, and scientific networks. It is common for several research teams to collaborate on the same project. The formation of teams of scientists, and the cooperation and collaboration between them, is usually encouraged by public administrations when financing the development of research projects.
- *Interest in scientific controversies in the advancement of science, and the rhetorical skills of scientists* (Acevedo-Díaz and García-Carmona 2017; Adúriz-Bravo 2014; Hein 1961; McMullin 1987). The existence of different theories about the same phenomenon is a major stimulus for the advancement of science. When scientists discuss the ideas of others, they normally revise or update them and, at times, new theories emerge or the path opens for other studies that broaden the field of research about the question being analyzed or other related ones. Innovative experimental techniques are usually developed during the course of such processes. Scientific controversies show the tentative and dynamic nature of science in permanent (re)construction, although sometimes, there is stagnation. For the ideas, models, and theories of scientists to be accepted by the scientific community, they must be based on verifiable evidence. They must also be expounded in the simplest way

possible for them to be understood. Therefore, in situations where different theories on the same phenomenon compete, it is likely that the scientist (or team of scientists) with the greater argumentative and persuasive capacity, even without their theory being valid, will gather more followers.

- *Scientific communication* (Acevedo-Díaz and García-Carmona 2017; Nielsen 2013; Spektor-Levy et al. 2009). Scientific communication plays an important role in scientific practice. It is the way scientists present their scientific advances for them to be subjected to scrutiny by the scientific community (peer review, discussion forums, the importance of rhetoric for persuasion, etc.). It has its own language, using a variety of semiotic registers (technical and systematic language, symbols, graphs, tables, equations, diagrams, etc.). The results of scientific research are usually reported through books, articles in specialized journals, and communications in congresses. The mass media also spread news about scientific advances. However, the content of science news may be biased by the interpretation made by journalists, or by a lack of rigor in their presentations since they are trying to reach as many people as possible whatever their level of scientific culture.
- *Role of the scientific community in the acceptance of new knowledge* (Abd-El-Khalick 2012; Acevedo-Díaz and García-Carmona 2017; Kuhn 1962). Scientific knowledge as the final product of science can be considered to be objective, but its construction and establishment processes are impregnated with subjectivity. Scientists tend to be skeptical of new discoveries and ideas, and apply control mechanisms to improve the objectivity of their conclusions (peer review, discussion forums, etc.). Therefore, the establishment of new knowledge requires approval by the scientific community (processes of intersubjectivity). For this reason, changes in science are not immediate but are preceded by discussions and, sometimes, disputes between scientists, where reasons that are rational coexist with others of a personal, social, or emotional nature. All this can hinder or delay the advancement of science for a certain time. Once accepted, however, the new knowledge is usually solid and durable, although susceptible to future modifications.

3 A Proposal of Pedagogical Principles for Science Teaching Based on the Nature of Scientific Practice

In the following subsections, we make an educational transposition of the aspects of the nature of scientific practice discussed above, in order to outline 10 essential pedagogical principles for science teaching in secondary school. Each principle is established with the support of the science education literature and is accompanied by a question or questions that incite metacognitive reflection about the aspect of scientific practice involved.

3.1 Formulating Questions

If all scientific research begins when a question is posed, learning science should always be guided by questions that are suggestive, and, as far as possible, investigable by the student. In this regard, two ways of incorporating questions into science teaching should be considered: questions posed by the teacher and questions posed by the student. Regarding the first way, Graesser et al. (2010) considered that good questions are those that make students aware that they are facing an obstacle to their understanding. According to Osborne (2014), the formulation of questions that make students reflect on their scientific ideas may also help concretize their efforts in constructing new learning. Consequently, a basic teaching skill for science teachers should be to know how to pose questions that incite curiosity in their students so that they want to learn about a phenomenon through scientific inquiry appropriate for their educational level (Cruz-Guzmán et al. 2017; Harlen 2012).

With regard to students, it can be said that they have an innate capacity to ask questions (Hayes 2009); however, this must be strengthened and improved in science education (Chin and Osborne 2008). In effect, students usually ask questions that are mainly oriented towards descriptions and causal explanations, but hardly ever directed towards verifications or evaluations (Roca et al. 2013). Consequently, they should be taught to recognize and ask questions that are scientifically approachable through inquiry. In this sense, Sanmartí and Marquez (2012) argued that scientific inquiry should not be reduced to find a response experimentally, but it should also allow the student to review her/his knowledge in order to improve the formulation of the inquired question or to propose new questions.

Some examples of questions for students to make meta-cognitive reflections about the role of formulating questions in scientific research might be:

- What importance do you think asking questions has had (and has) on the development of science?
- What characteristics do you think questions should have so that they can originate scientific inquiry?
- In what way do you think that the characteristic or type of question can condition the research procedure scientists will follow to be able to answer it?

3.2 Creativity and Imagination

If scientists are creative and imaginative when developing their research, in a science class learning, teachers should present situations that activate students' ingenuity, inventiveness, originality, and divergent thinking. This is an issue that has barely been addressed by science educators or science education researchers (Kind and Kind 2007). Practically, there have only been theoretical and diagnostic approaches to beliefs in this sense (Hu and Adey 2002; Liu and Lin 2014). The development of this principle requires closed learning situations to be avoided, i.e., those that set tasks which only demand univocal and/or repetitive responses parroting those previously dealt with in class. This suggests proposing open activities which, with the appropriate educational orientations, can stimulate students to make their own contributions. This could be done by posing interesting problems for them to inquire into, by their imagining solutions to an open problem, proposing their own models in the study of a phenomenon, designing experiments to test hypotheses, and even constructing simple artifacts that fulfill a certain function (e.g., a home-made balance or a sand-clock with which to make measurements, representing basic mechanisms with household materials, building stable structures using fragile materials, etc.). The latter would further contribute to the development of engineering skills by students, while it would also provide a means of employing science and mathematics in creative ways to solve real problems (NGSS 2013).

Longshaw (2009) noted that creativity can be stimulated in science class with simple exercises. In one of her interventions in class, she put the following question to her 13–14-year-old students: "If you were a metal, which one would you be and why?" The result was this:

> A lot of the boys wanted to be iron (because of its strength). Many of the girls chose the precious metals because of their association with jewellery and perceived value. But the one that made the most impact on me was the student who chose aluminium "because it is the only time I will be light [weight]!" (Longshaw 2009, pp. 93-94).

The following might be some questions for students to reflect meta-cognitively on the aspect of scientific practice that is involved in this pedagogical principle:

- What importance do you think the creativity and imagination of scientists has had (and has) in the development of science?
- In what way do you think the creativity and imagination of scientists manifests itself?
- What differences and similarities are there between the creativity of scientists and artists?

3.3 Experimentation

If experimentation is one of the essential practices of scientific research, conducting experimental activities should have a prominent role in learning science. Experimental activities can be understood as those in which students inquire into and develop an understanding of the physical world through direct experiences with the phenomena and through the manipulation of objects, materials, observation, and measurement instruments. In the context of education, different types of experimental activities can be distinguished according to the question formulated (Harlen 2013). Cañal et al. (2016) distinguished the following types: (i) observing/exploring a phenomenon (e.g., "how does … happen?), (ii) determining cause-effect relationships (e.g., how do you think … influences …?), and (iii) designing methods to do checks, observations, or measurements (e.g., how would you measure /verify…?). The ideal is to implement the experimental activities as small inquiries. These may be of different types, as will be seen in the next principle. Sometimes, it may be of interest for the teacher to carry out the experiment in order to show the students a phenomenon and then encourage them to reflect upon it. In any case, it is advisable to opt for experimental activities with clear and specific objectives appropriate for a science class (García-Carmona et al. 2018). Experimental activities should also be combined with other types of activities to complement and strengthen the learning that is aimed for (Millar 2010).

The following might be some questions for students to reflect meta-cognitively on the role of experimentation in science:

- Why do you think science experiments are carried out?
- Can scientific knowledge be constructed without experiments? Why?
- How would you explain what scientific experimentation consists of?
- What differences do you find with other types of experiments (e.g., experimentation by artists, chefs, artisans …)?

3.4 Procedural Diversity

If scientists use a variety of approaches and strategies to generate knowledge, thus demonstrating the non-existence of an algorithmic, unique, and universal scientific method, then science education should promote problem-solving and scientific inquiries which, with the appropriate teaching approach, present (i) a challenge for the students and (ii) are posed so that the students can use a variety of their own strategies in addressing them. This principle implies that, in science teaching, one should no longer speak about “the scientific method and its stages.” In addition, teaching plans should avoid algorithmic and uncritical problem solving, as well as “recipe”-type laboratory experiments with which the students end up focusing on completing the instructions rather than on learning about what they are doing and why they are doing it (Hodson 2005).

Students always need some type of guidance or orientation when they carry out scientific inquiries (Arnold et al. 2014; García-Carmona et al. 2017). These are usually more effective the greater the degree of guidance (Bunterm et al. 2014; Kirschner et al. 2006). However, students’ autonomy in learning science through inquiry increases when they have an ongoing experience with this approach (Bertsch et al. 2014; Koksal and Berberoglu 2014). Consequently, the problems and inquiries should be presented with different levels of guidance in class, depending on the students’ capabilities, previous ideas, and experience with this approach, but always with some kind of challenge for them. In this regard, Banchi and Bell (2008, p.27) proposed four levels of inquiry: (i) confirmatory inquiry, where the teacher provides students with a question, and indicates the procedure to obtain previously known results, so as to confirm or reinforce a scientific idea, or to practice the acquisition of specific skills and the organization of data; (ii) structured inquiry, where the question and the procedures are still set by the teacher, but the students have to develop a scientific explanation from the data that is recorded; (iii) guided inquiry, where the students design and follow their own procedures to collect data and draw conclusions in response to a question posed by the teacher, and with the aid of an open work script; and (iv) open inquiry, where the question and the procedure for the inquiry are proposed by the students.

The following might be some questions for students to reflect meta-cognitively on the role of procedural diversity in science:

- In many science textbooks, science news websites, etc., one can find the phrase “the scientific method.” Do you think that all scientists follow the same method in their research? Argue your answer.
- Do you think the same research problem can be solved following different procedures? Explain your answer.
- If two teams of scientists investigate the same problem but follow different procedures, do you think they will reach different results? Why?
- If you were a scientist, what criteria would you use to choose the procedure for solving a research problem? Explain your answer.

3.5 Errors as Opportunity

If errors are an inherent part of scientists’ work, and they take them as something normal in their practice and therefore try to learn from and correct them to then be able to advance in their research, science education should “normalize” errors in the development of students’ scientific competencies, i.e., accept them as opportunities to learn and improve. Although in real scientific practice, errors are accepted as being inevitable and natural, and scientists deal with them constructively, science education unfortunately continues to promote a vision of errors as being negative or equivalent to failure.

According to Allchin (2012), if scientific knowledge changes, it is partly because scientists first made errors (in measurement, calculation, assumption and/or testing of hypotheses, data interpretation, etc.). Therefore, if the intention is for students to understand and accept scientific knowledge as being reliable at the same time as changeable, they should be taught about the limits of science and the fundamentals of scientific errors. Zachos et al. (2003) suggested that science education should encourage students to develop a sensitivity, understanding, and competency to be able to deal constructively with the role of errors while learning. All this implies that science educators should propose, on the one hand, class activities dealing explicitly with errors (for example, calculation of the errors of measurement in experiments, analysis of errors made by scientists in the past and how these were corrected, etc.), and on the other hand, meta-cognitive activities that help students become aware of their errors and deal with them properly so as to progress in their learning (García-Carmona 2012b; Schraw et al. 2006).

The following might be some questions for students to reflect meta-cognitively on the role of errors in science:

- Sometimes, we make errors but are unaware of it. How do you think scientists become aware that they have made an error?
- What do you think scientists do to avoid making errors in their research?
- What do you think scientists do when they detect errors in their research?
- What do you think about the following statement: “The best scientists are those who do not make errors in their research”?
- If scientists make errors in their research, how do you think this influences the development of science?

3.6 Modeling

If an important part of scientific practice is dedicated to constructing, evaluating, and improving models to represent, explain, and make predictions about natural phenomena, science education should integrate modeling as an essential and common activity in science classes. For years, scientific modeling has occupied a prominent place in research about science education (Gilbert and Justi 2016), but its transfer to regular teaching practice in science classes is still very limited. Among other reasons, this may be due to the nature of the scientific models and modeling being ontologically and epistemologically complex and multifaceted (Acevedo-Díaz et al. 2017b). Models and modeling in science are therefore difficult to understand not only for students (Grosslight et al. 1991; Harrison and Treagust 1998) but also for science teachers (Justi and Gilbert 2002) and even scientists themselves (Wong and Hodson 2009).

In science education, the use of analogies is one of the commonest and most effective resources for students to learn about scientific models and modeling (Aragón et al. 2014; Oliva et al. 2007). Another interesting approach was proposed by Gouvea and Passmore (2017). They suggested distinguishing between scientific models’ representative function (“models of”) and cognitive or epistemic function (“models for”) in order to deal with modeling in science teaching. For example, in connection with the study of the atom, the development of a “model of” would focus on how to represent a real atom, while a “model for” would explain and predict the formation of chemical bonds. The key to addressing these two modeling perspectives would therefore lie in formulating the crucial questions to address in class. Thus, with the question “What is an atom like?”, there is a demand for the development of a model of the atom, whereas, for example, with the question “How can you explain the chemical bond of a sodium atom with a chlorine one?”, there is a demand to construct a model to explain how atoms behave in the presence of other atoms.

The following might be some questions for students to reflect meta-cognitively on the role of modeling in science:

- Why do you think scientists develop models of the phenomena they study?
- What do you think about the following statement: “Scientific models represent in detail the objects or phenomena they are referring to”?
- What relationship do you think there exists between the model or models and the theory that scientists construct about a particular phenomenon?
- Do you think scientists construct more than one scientific model when studying a phenomenon? Argue your answer.

3.7 Cooperation and Teamwork

If science is the result of a collective process in which scientists usually organize themselves into teams in order to conduct their research cooperatively and collaboratively, science education should encourage students to also cooperate and collaborate with each other as they learn from (and about) science and doing science. This principle is consistent with psychological approaches to a form of learning that is based on social constructivism (Vygotsky 1985). In this way, learning will develop through a collective process using permanent dialog and interaction between individuals of a similar cognitive level[4] (interaction between students) and with an expert or someone of a higher cognitive level (student-teacher interaction). According to Salmerón (2013), the interaction between several students to answer a question often produces responses that are better argued since the students have to make the effort to develop a common opinion that combines their different views. Teamwork is therefore conducive to generating a climate of collaboration and cooperation in class where the students, with support and appropriate guidance from the teacher, negotiate meanings by exchanging ideas, opinions, assessments, etc., in order to reach conclusions that provide new learning. Obviously, it will not always be possible for the teams to reach consensus. This must be managed with normalcy, favoring the potential existence of different positions within a given team. In addition, it may provide an opportunity for the students to reflect on the difficult process of consensus for the acceptance of new knowledge in science. Various studies have revealed the positive contribution of students working in small teams to learn about NOS (Acevedo-Díaz et al. 2017a; García-Carmona and Acevedo 2016).

The following might be some questions for students to reflect meta-cognitively on the role of cooperation and teamwork in science:

- What importance do you think collaboration among scientists in their research has for the advancement of science?

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[4] It is what is known in Vygotsky’s terminology as the Zone of Proximal Development.

- Do you think there may be drawbacks when scientists work as a team? Justify your answer.
- What do you think happens in a research team when its members do not all agree about how to do an experiment, or how to interpret its results?
- Do you think it is necessary for one scientist to act as the chief in research teams? Why?

3.8 Argumentation and Discussion

If, in research teams and the scientific community in general, scientists discuss their ideas and have to convince their peers about them, they need to develop good arguments (i.e., based on data and by using good rhetoric), and then the discussion of ideas based on argumentation should be a central topic in science classes. This principle is closely linked to the previous one and suggests that the teacher should pose questions about which students are required to make responses based on scientific evidence, also taking into account aspects of NOS, and expressing them as clearly and convincingly as possible. The educational interest of encouraging argumentation when learning science has been treated in depth in the science education literature (Erduran and Jiménez-Aleixandre 2008). There is a strong correlation between knowledgeable views about NOS and the presentation of quality arguments (McDonald 2017). Indeed, explicit reflection on controversial scientific and socio-scientific issues, both historical and contemporary, in order to learn about NOS improves students' argumentation skills (García-Carmona and Acevedo 2016, 2017; Acevedo-Díaz et al. 2017a; Khishfe 2014). In addition, a key factor in improving arguments is to promote critical discussion among the students so as to put their arguments to the test. To this end, it is useful to promote class activities with questions that require the development of scientific arguments, and which are implemented through cycles of (1) preparation of initial arguments in small groups, (2) exposure in a large group to the various initial arguments for their evaluation and discussion, and (3) review and re-elaboration of the initial arguments, again in small groups, after the debate.

The following might be some questions for students to reflect meta-cognitively on the role of argumentation and discussion in science:

- What role do you think discussions and controversies among scientists have for the advancement of science?
- What characteristics do you think a scientific theory should have to be more popular within the scientific community than other rival theories?
- Why do you think the ideas of some scientists are more convincing than others when they are studying some phenomenon independently?
- What do you think happens in the scientific community when there are several theories to explain the same phenomenon?

3.9 Communication

If scientists read and interpret their peers' studies, and write up reports with the results of their research which they then publicize through books, journal articles, or orally in forums and conferences, science education should prioritize the development of students' skills in communicating their ideas, as well as in the critical reading of scientific news provided by the different media.

The development of such skills is key to achieving an adequate scientific literacy (Cañal et al. 2016; NGSS 2013). Spektor-Levy et al. (2009) suggested that scientific communication skills require explicit guidance in the form of a spiral, including tasks of information searches, reading, science writing, information representation, and representation of the knowledge acquired.

Linked to the principle of argumentation and discussion, a good way to develop students' scientific communication skills is to ask them to prepare short reports with the results of their inquiries and, in general, of their responses to the various tasks they did in class. Although these reports should be in a certain way coherent with those that scientists write, they primarily have to respond to educational purposes, i.e., they must especially help the students to reflect and to structure their own ideas about the aspects that have been addressed in order to improve their comprehension of them (García-Carmona 2008). Also, it is interesting to get students accustomed to presenting, both orally and with the support of ICTs, the results of their scientific inquiries to their classmates (Cañal et al. 2016).

Since the mass media are the main source of information about science for most citizens (Hodson 2008), critical analysis of scientific news should be a regular activity in science classes (García-Carmona 2014; Jarman and McClune 2007). Some studies have shown the educational potential for learning about NOS of analyzing scientific news reported by the media (García-Carmona and Acevedo 2016; Leung et al. 2015; Shibley 2003) or posted on social networks (Huang et al. 2014). The analysis of primary and secondary sources of information of scientific research is also effective for learning about the nature of scientific communication (Klucevsek and Brungard 2016).

The following might be some questions for students to reflect meta-cognitively on the role of scientific communication:

- What media do you think that scientists use to communicate?
- Why do you think scientists publish their research findings in journals, books, etc.?
- What do you think is the purpose of scientific congresses or meetings?
- What differences do you think there are between scientific news published in the media (newspapers, TV, websites, social networks …) and those published in scientific journals?
- What criteria do you think the scientific news published in the media should have in order to be reliable?

3.10 Evaluation

If the work of a scientist (or team of scientists) is continuously scrutinized both by themselves and by other scientists through rigorous evaluation processes (peer review, critical articles, and replies to previous publications, etc.), science education should promote students' development of self-evaluation and co-evaluation skills to apply throughout their learning process. This principle in some way permeates or is implicit in all the others, since all the actions and tasks proposed for the proper development of these processes require evaluation.

Regarding self-evaluation, the activities carried out in a science class should be accompanied by explicit questions for the students to reflect on the progress and difficulties they have as they learn, as well as on the possible causes of those difficulties and the strategies to overcome them (García-Carmona 2012b). This will favor formative evaluation. Regarding co-evaluation, it is very interesting to promote peer evaluation processes or similar in science classes in order to get the students used both to making critical and constructive assessments of their peers' ideas, proposals, etc., and to receiving such assessments. Implementing this evaluation perspective has shown itself to be effective in science class (Cruz-Guzmán et al. 2017; Klucevsek and Brungard 2016).

The following might be some questions for students to reflect meta-cognitively on the role of evaluation in scientific research:

- How important do you think it is for scientists that their peers evaluate their research?
- Before research findings are accepted for publication, they are usually evaluated by anonymous peers (at least two scientists who neither know each other nor the authors of the research). What is the interest of doing it this way?
- Many scientists use a diary to record everything about their research. What use do you think this may have for their work?

4 Epilogue

For some years, the international science education community has been proclaiming NOS as basic content of citizens' scientific literacy. In this regard, there have been various educational approaches as to what and how to teach about NOS, with some of them being supported by the results of empirical research. Also, most school science curricula and reports for the improvement of science education argue for students to become familiarized with the skills typical of actual scientific practice. This suggests that students should also familiarize themselves with the nature of that practice, i.e., that they acquire meta-knowledge about scientific practice. However, NOS has for a long time been identified with the nature of the scientific knowledge that is produced so that most studies of the comprehension and teaching of NOS have left out many characteristic epistemic and non-epistemic features of scientific practice.

This is of course not an encouraging panorama in which to achieve the scientific literacy that is desirable for today's citizens. From a utilitarian point of view, the results of science education research will only make sense if they end up being transferred to the everyday activity of science classes. Consequently, as science education researchers, we must make every effort possible for this transfer to occur, and thus narrow the glaring gap that currently exists between research and actual teaching practice in science education.

The idea for the present study arose from such concerns. If we want science students to acquire both an informed understanding of aspects of NOS as well as scientific practice skills, and if we assume that the nature of scientific practice is a subset of the construct we call NOS, then why not take an approach to science teaching that is inspired by real scientific practice so that students can learn about the nature of scientific practice while they are learning science? The answer to this question crystallized into 10 pedagogical principles for science education in secondary school (12–18 years old). These were developed on the basis of an in-depth reflection on the part of the authors, and a thorough review of the literature, the premise being that those principles enable dynamics and strategies of teaching to be promoted in science class which are consistent with the values of education. In addition, their implementation in science class requires an explicit approach based on meta-cognitive reflection about the aspects of the nature of scientific practice that are involved. It is also necessary to emphasize that the development of the pedagogical principles in science class should be adapted to the needs and circumstances of each particular educational level and/or context. This will depend on the students' abilities and experiences with the school scientific activity and their initial levels of understanding about the nature of scientific practice, among other factors. In any case, ideally, the pedagogical principles proposed should be progressively developed throughout the secondary school. In this regard, in future studies, it would be interesting to address how that progressive introduction of the principles in each level of this educational stage could be made, and to analyze how it works.

We are aware that more and/or better pedagogical principles might be established for the intended purpose, although we believe that the present proposals could constitute a good starting point from which to advance in the line of work that we posit. In our opinion, an ideal science teacher would be one who integrates into their daily teaching practice at least the principles that have been described. However, we are realistic and know that there are numerous obstacles to significant changes in science teaching, and that, if such changes do occur, they are usually slow. In this regard, although they are related, the proposed pedagogical principles should be considered independently for their gradual incorporation into teaching practice. In other words, one way of conceiving the described proposal is for science teachers to begin by integrating just a few of the principles and gradually increase the number of principles as they become assimilated and ingrained in their normal teaching work.

Finally, our desire is that the proposal we have presented be submitted to critical and constructive analysis on the part of all those colleagues who are interested in improving students' comprehension of aspects of NOS in general, and of the nature of scientific practice in particular.

Acknowledgements This study was supported by the Ministry of Economy, Industry and Competitiveness (Spain) under grant EDU2017-82505-P.

Compliance with Ethical Standards

Conflict of Interest The authors declared that they have no conflicts of interest.

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