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SI: NATURE OF SCIENCE

A Critical Review of Students' and Teachers' Understandings of Nature of Science

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Abstract
There is widespread agreement that an adequate understanding of the nature of science (NOS) is a critical component of scientific literacy and a major goal in science education. However, we still do not know many specific details regarding how students and teachers learn particular aspects of NOS and what are the most important feature traits of instruction. In this context, the main objective of this review is to analyze articles from nine main science education journals that consider the teaching of NOS to K-12 students, pre-service, and in-service science teachers in search of patterns in teaching and learning NOS. After reviewing 52 studies in nine journals that included data regarding participants' views of NOS before and after an intervention, the main findings were as follows: (1) some aspects of NOS (empirical basis, observation and inference, and creativity) are easier to learn than others (tentativeness, theory and law, and social and cultural embeddedness), and subjective aspects of NOS and "the scientific method" seemed to be difficult for participants to understand; (2) the interventions most frequently lasted 5 to 8 weeks for students, one semester for pre-service teachers, and 1 year for experienced teachers; and (3) most of the interventions incorporated both decontextualized and contextualized activities. Given the substantial diversity in the methods and intervention designs used and the variables studied, it was not possible to infer a pattern of more-effective NOS teaching strategies from the reviewed studies. Future investigation should focus on (a) disentangling whether a difference exists between the easy and difficult aspects of learning NOS and formulating a theoretical explanation for distinguishing the two types of aspects and (b) assessing the effectiveness of different kinds of courses (e.g., history of science, NOS or informal) and strategies (e.g., hands-on vs. drama activities; SSI vs. HOS).

1 Introduction

Although there are differences among authors and documents regarding the meaning of scientific literacy (see Dillon 2009; Roberts and Bybee 2014), there is unanimous agreement that an adequate understanding of the nature of science (NOS) is a critical component and a

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major goal in science education (e.g., Millar and Osborne 1998; Osborne et al. 2003; Wahbeh and Abd-El-Khalick 2014; Lederman and Lederman 2015; Kampourakis 2016; Cofré et al. 2014). Lederman (2007) defined NOS as "the characteristics of scientific knowledge that are directly related to the way in which it is produced." The general science standards suggest that future citizens should be literate about science, that is, to be able to acquire the necessary scientific knowledge and to understand the interactions between science and society; this competency depends on understanding NOS. Indeed, the objective of helping students develop adequate understanding of NOS is "one of the most commonly stated objectives for science education" (Abd-El-Khalick and Lederman 2000a).

Despite this worldwide consensus about the importance of NOS for scientific literacy, research studies consistently indicate that most science teachers and students do not possess an adequate understanding of NOS (e.g., Deng et al. 2011; Lederman and Lederman 2014). Many studies regarding NOS instruction and understanding have shown that explicit and reflective teaching is the most effective approach for improving teachers' and students' NOS views (Abd-El-Khalick and Lederman 2000a, b; Morrison et al. 2009; Bell et al. 2011; Cofré et al. 2014; Van Griethuijsen et al. 2015). However, there is still much work to be done to identify the best model for teaching NOS (Lederman and Lederman 2014), and there is still a lack of consensus on the most important features of an instructional model that will generate a better understanding of NOS among students and teachers. For example, we still lack knowledge of why some aspects or characteristics of NOS are more difficult to understand than others (Mesci and Schwartz 2017); we do not clearly know whether there is some connection among certain aspects that allow them to be learned in an implicit way (e.g., Seung et al. 2009; Pavez et al. 2016), and we do not know the most effective type of instruction for teaching NOS (e.g., Cofré et al. 2014) or what the real relationship is between students' NOS understanding and scientific concept learning (Lederman 2007; Peters 2012; Michel and Neumann 2016; Cofré et al. 2018).

With the present review, we aim to contribute to the discussion about how to teach NOS and the main factors affecting NOS learning. Therefore, the main objectives of the review were (1) to analyze a representative sample of literature that considers the teaching of NOS at different educational levels (including K-12 students and pre-service and in-service science teachers) and (2) to search for patterns of teaching characteristics and NOS learning gains from pre- to post-intervention.

2 Theoretical Background

2.1 NOS Conceptualization

Changes in the conceptualization of NOS within philosophical, sociological, and historical circles are reflected in the ways the science education community has defined the phrase "NOS" over the past 100 years (Abd-El-Khalick and Lederman 2000a). Some authors have broadly defined NOS understanding as "to know how science works" (e.g., Wellington and Ireson 2008; Clough 2011). Lederman (2007) advocated using the phrase "nature of scientific knowledge" rather than NOS to avoid confounding NOS with scientific inquiry, although this aspect of science and especially "the scientific method" has been considered an aspect of NOS in many NOS studies (e.g., Liang et al. 2009; Schwartz et al. 2004; Seung et al. 2009; Bell et al. 2011).

Science educators have reached a certain degree of consensus about NOS in the past few decades (e.g., McComas 1996; Osborne et al. 2003; Lederman 2007; Niaz 2009; Kampourakis 2016). For example, McComas and Olson (1998) reviewed eight international science standards documents from four countries, and despite the great diversity of elements associated with NOS in the official documents (almost 40 documents were included), they found a notable level of commonality regarding the aspects of NOS currently recommended to be taught to precollege students (however, see Olson 2018, for a new assessment of the inclusion of NOS in standards documents worldwide). A similar consensus on NOS aspects has also been reached by another group of leading international experts, including science educators, scientists, historians, philosophers, and sociologists of science (Osborne et al. 2003). This conceptualization has been referred to as the "general aspects" conceptualization of NOS or the "consensus view" (Kampourakis 2016).

According to this consensus view, there are some general NOS aspects (usually between seven and ten, depending on the authors) that can effectively be taught in the school context. The main objective of this conceptualization is to address students' misconceptions of how science works and what scientific knowledge is. However, this conceptualization has been criticized as insufficient and misleading, and different alternative approaches have been proposed (e.g., Allchin 2011; Irzik and Nola 2011; Matthews 2012; van Dijk 2011).

For example, Clough (2011) stated that because science is such a complex activity, NOS issues should be presented as questions rather than as specific NOS tenets that students should learn. According to Clough, this way of teaching NOS encourages students to think more deeply about the contextual nature of scientific work. His proposal focuses not only on what elements should be taught but also on the way in which NOS should be taught (see also the next section). In this sense, it should be clarified that according to authors who promote the consensus view of NOS, the creation of a list of aspects of NOS has never implied that these characteristics should be learned without being discussed by the students (Schwartz et al. 2012). Another substantive issue is whether there truly is a consensus that science is based, at least partially, on empirical evidence, that scientific knowledge changes over time or that observations are theory-laden (e.g., Matthews 2012; Romero-Maltrana et al. 2017). Matthews' (2012) proposal to use features of science instead of NOS is based on the idea that most of the elements of the consensus view need to be "more philosophically and historically refined and developed in order to be useful to teachers and students," and he proposed a list of 18 features of science to be discussed with students and science teachers. This desire for a more accurate definition of the characteristics of science is certainly praiseworthy. However, although the "general NOS aspects" conceptualization has been widely used, there is no evidence that the general aspects lead to distortions of teachers' and students' views of science (Kampourakis 2016).

Some authors also believe that the "general aspect" conceptualization of NOS has weaknesses, because it is blind to the differences among scientific disciplines. The family resemblance approach is represented by the conceptualization of NOS by Irzik and Nola (2011), who attempted to overcome these problems. This approach relies on the idea that the members of a family can each resemble one another in some respects, but not in others. In the context of science, this idea suggests that even if there are some characteristics common to all sciences, these characteristics cannot be used to define science itself. Irzik and Nola (2011) suggested four specific categories that are open-ended: (a) processes of inquiry, (b) aims and values, (c) methods and methodological rule, and (d) products. Although the authors claim that the family resemblance approach can capture the dynamic and open-ended NOS much better than the consensus view, it is also clear that it would be a much more complex approach to implement in the school context (see also Erduran and Dagher 2014).

Based on the previous discussion, we adopt an instrumental conceptualization of NOS in this review. That is, we understand NOS as a set of characteristics of science that is important for teaching science in school and that is shared to a greater or lesser extent by the different scientific disciplines. In this article, we adopt a "consensus view" of the teaching of NOS: we believe that it is possible to describe scientific knowledge using a limited group of aspects or characteristics that may vary depending on the author but that, in general, include the human elements of science, the products of science, and the bounds of scientific knowledge (McComas 2015). The use of this approach means that in our review, we included not only studies that work with the main NOS tenets but also all the articles that met our search criteria (see the methods section); further, the theoretical framework that we used to analyze and discuss the studies included the teaching and learning of NOS as the sum of different topics or issues (e.g., Lederman 2007; Clough 2011; McComas 2015) rather than the participants' holistic philosophical views.

2.2 Teaching NOS to Teachers and Students

There has been a substantial amount of research on NOS in recent years, which is reflected in the numerous reviews and analyses of the current status of the topic (e.g., Lederman 2007; Hodson 2009; Deng et al. 2011; Abd-El-Khalick 2012; Khishfe 2012; Lederman and Lederman 2014) as well as practical recommendations for developing pedagogical content knowledge (PCK) for teaching NOS (Aydin et al. 2013). According to this literature, science teachers, regardless of their number of years of teaching experience (pre-service and in-service), level (elementary or secondary) and discipline, do not possess an adequate understanding of the different aspects of NOS (see previous section), irrespective of the instrument used for assessment (Lederman and Lederman 2014). The erroneous conceptions most frequently demonstrated include the following: (1) hypotheses become theories and theories become laws; (2) science is an objective enterprise, and scientists do not use their experience and background to analyze results or propose explanations; (3) scientific knowledge is an immutable truth; and (4) only one scientific method exists. Consequently, most of these misconceptions are also held by students (see also McComas 1996; Hodson 2009; Lederman and Lederman 2014; Kampourakis 2016).

In regard to teaching NOS, some evidence exists that students in a constructivist class have a greater chance of developing more sophisticated views about NOS than students in a traditional class (Smith et al. 2000). More specifically, we know that for effective NOS instruction, we need to recognize NOS as an important aim of science education and plan and assess its teaching in an explicit way (Lederman 2007; Clough 2011; Clough and Olson 2012). However, although a large amount of empirical data generated in recent decades suggests that explicit and reflective way of teaching NOS as the most effective method (e.g., Abd-El-Khalick and Lederman 2000a, b; Lederman 2007; Matkins and Bell 2007; Bell et al. 2011; Pavez et al. 2016) and emphasizes the importance of addressing NOS across diverse contexts and in alignment with conceptual change (Clough 2006; Herman, Clough and Olson 2012), the field still lacks robust, empirically based comparisons of exactly which nuanced aspects of NOS instruction (e.g., contextual features, duration) best promote NOS understanding among students and teachers. Much of this lack of consensus could be due to the broad range of methods and contexts used to teach NOS and the lack of a clear nomenclature for presenting the findings (however, see McComas et al. 1998; Khishfe and Lederman 2006; Clough 2006; Lederman 2007).

The results of interventions to teach NOS often focus on describing the courses in which the interventions were conducted, the contexts in which they were used, or the teaching strategies and activities that were included. In terms of courses, the literature has identified different types of courses in which NOS can be taught: science method courses, science content courses, authentic science experiences (e.g., internships in research laboratories), informal science courses (e.g., science camps), history or philosophy of science courses, and self-contained NOS courses, also called pull-out courses (Lederman 2007; McComas et al. 1998; Clough and Olson 2012; Cofré et al. 2014). Of these types of courses, science method courses are among those used most often to change pre-service teachers' understanding of NOS (e.g., Akerson et al. 2000; Abd-El-Khalick and Akerson 2004, 2009; Bell et al. 2011; Matkins and Bell 2007; Seung et al. 2009; Akerson et al. 2012; Herman et al. 2013a, b). It is more difficult to identify the types of courses that are most frequently used to teach NOS to in-service science teachers and students.

In the context of courses, one of the most frequently used and clearest ways to determine the activities or strategies used for teaching is the amount of scientific content the course includes (Clough 2006). Some authors claim that contextualized or integrated activities in which NOS instruction is embedded within science content are the best for improving students' and especially teachers' understandings of NOS (see Clough 2006 for a review). Meanwhile, studies of students that consider the instructional context have not shown a clear pattern (Khishfe and Lederman 2006, 2007; Bell et al. 2011), and some studies focusing on teaching have even shown that black box activities (Lederman and Abd-El-Khalick 1998) yield more significant results than integrated activities (Seung et al. 2009; Donnelly and Argyle 2011; Pavez et al. 2016, Cofré et al. 2018).

Nevertheless, this category of studies focusing on activities or context only describes whether the subject matter and NOS are both delivered in lessons but does not discuss the methods or strategy through which content is delivered or taught. Historical dramatizations, replications of historical experiments, and lectures about the history of a scientific discovery are all contextualized or integrated activities, but they use very different instructional strategies for teaching NOS. Some of the strategies used for students and teachers include examinations of socio-scientific issues (e.g., Matkins and Bell 2007; Bell et al. 2011; Wong et al. 2008); workshops and hand-on activities structured for conceptual change (e.g., Seung et al. 2009; Donnelly and Argyle 2011); and group drama activities (Boujaoude et al. 2005). However, the type of activity or strategy used for teaching NOS has rarely been included as a study variable. A notable exception is a study by Akerson et al. (2014b) in which four teaching strategies were used in four types of method courses. Although the efficiency of the courses was not explicitly compared, the study was useful for relating different types of strategies with different levels of improvement in different aspects of NOS.

In light of the situation discussed above, we believe that further research is needed to fill some gaps in the knowledge about teaching NOS, specifically on the following issues:

1) For which NOS aspects do students and teachers hold the most naïve and the most informed ideas at the beginning of teaching interventions?

2) Which ideas about NOS held by students and teachers offer the most opportunities for improvement and which improve the least after an NOS instructional intervention?
3) What is the optimal duration for an NOS instructional intervention for students and teachers?
4) What are the characteristics of NOS instruction in terms of the courses, context, and strategies used?
5) What are the most effective strategies for teaching NOS to students and teachers?

3 Methods

3.1 Selection of Studies for Review

The aim of this literature review was to identify the main instructional characteristics of interventions for increasing understanding of NOS in K-12 students and elementary and secondary science teachers. For this purpose, we were interested in studies in which NOS understanding was evaluated at the beginning and the end of an instructional intervention; consequently, we only selected empirical studies for review. We did not include articles in which the participants' views or understandings of NOS were evaluated only once or the teaching of NOS was studied without reference to the participants' understanding. We also did not include studies in which the focus of the intervention or evaluation was scientists or in which only college students who were not student teachers were studied because our review focused on supporting the work of science educators and school teachers who want to teach NOS.

We searched for papers in the Educational Resources Information Center (ERIC) database and from a list of 9 academic journals: *Science Education*, *Science & Education*, *Journal of Research in Science Teaching*, *International Journal of Science Education*, *Research in Science Education*, *Journal of Science Teacher Education*, *International Journal of Science and Mathematics Education*, *School Science and Mathematics*, and *Journal of Science Education and Technology*. Because the most recent critical review of teaching and understanding NOS was the seminal paper of Abd-El-Khalick and Lederman (2000a), we decided that our review should start where that paper ended. Therefore, all searches were made between January 2000 and September 2018. We searched for and selected papers according to the following criteria: (1) only empirical papers were included (theoretical papers were excluded from this review) and (2) papers that analyzed teachers' or students' views of NOS without providing an instructional intervention were also excluded from this review, and only pre-test and post-test studies were included. We analyzed the abstract of each article that included the words "course," "NOS," or "nature of science" and "students" or "teachers" in the title. Likewise, papers that did not provide any detailed quantitative data and/or qualitative descriptions of the specific aspects of NOS that were addressed and potentially improved after the intervention were also excluded from this review. Although this review is not intended to be a meta-analysis of the effectiveness of teaching NOS, we assumed that the studies reviewed were all effective, because there is a publication bias that reduces the likelihood that negative results will be presented in scientific journals (Lederman and Lederman 2016). That is, we do not have information on what courses, context, or strategies are not effective in teaching NOS, because these works are usually not published.

3.2 Focus and Review Approach

Different characteristics of the studies were analyzed to answer our research questions. These characteristics included the following: (a) the authors of the work, (b) the duration of the intervention, (c) the number of students or teachers who participated, (d) the type of course in which the research was performed, (e) the type of context in which the activities were used, and (f) the teaching strategies and curricular elements included. In addition, the grade was also recorded for the studies conducted with K-12 students. The type of context refers to whether NOS concepts in the activities were embedded within science content (contextualized or integrated) or were included within black box activities (decontextualized or non-integrated), such as those included in Lederman and Abd-El-Khalick (1998) (Clough 2006; Khishfe and Lederman 2006, 2007). Specifically, we followed Clough (2006) and recognized the difference between highly contextualized instruction (including the history of science or socio-scientific issues) and contextualized instruction (including content in another context, such as a laboratory activity). Finally, the results of each study were summarized according to the quantitative or qualitative findings that the authors presented. Specifically, most of the findings were reported as the number or % of participants in the informed or enhanced category of NOS understanding at the end of the interventions compared with the number or % at the beginning of the study.

4 Results and Discussion

In our review of studies published in nine journals from 2000 to 2018 (September), we identified 133 studies that included at least two of the keywords. Among these studies, 52 met the inclusion criteria (see the method section). Figure 1 shows the distribution of the studies at each educational level. In the following sections, we analyze and discuss the results within each educational level.

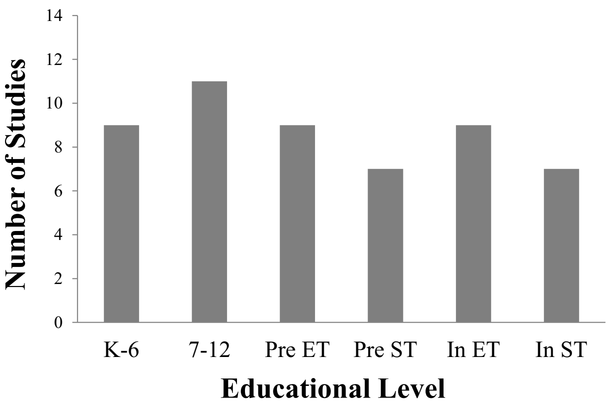

Fig. 1 Number (*n*) of studies analyzed by level of study. K-6 = elementary school students; 7–12 = middle and secondary school students; Pre ET = pre-service elementary teachers; Pre ST = pre-service middle or secondary teachers; In ET = in-service elementary teachers; In ST = in-service middle or secondary teachers

4.1 Understanding of NOS and Instructional Characteristics at the Elementary Level

Among the nine reviewed studies on elementary students' views of NOS, the most common interventions were content (six studies) and inquiry courses (three studies), which included only integrated activities (six studies) or both types of contexts (five studies). The most frequent instructional method was inquiry activities with reflection, which were included in six studies (Table 1). In general, only a few aspects of NOS were studied. The most frequently studied ones were tentativeness, observation and inference, creativity, and the empirical basis of science (all these were included in seven studies). Most students held naïve views about subjectivity at the beginning of the studies, and the best understood aspect before the intervention was empirically based science. At the end of the instruction, the students' views that showed the most improvement were the understanding of creativity, while the least improved views were the understanding of the difference between observation and inference and tentativeness. Most of the interventions (five studies) used the VNOS-D instrument, the shortest version of the VNOS questionnaire, to assess the students' understanding of NOS. Other instruments used are POSE (Perspectives on Scientific Epistemology Questionnaire) and NOSSI (Nature of Science and Scientific Inquiry questionnaire).

In a more in-depth examination of the results of some studies, we identified a pattern across multiple studies by Akerson and colleagues. For example, in a study that described views of NOS among 25 students from kindergarten to second grade who attended a Saturday science class, Quigley et al. (2010) found evidence that the students held naïve views on the subjective and socio-cultural aspects of NOS prior to the program. They also found that many students already held an adequately developed view of the empirical aspect of NOS at the beginning of the study. At the end of the study, the students had improved the most in their understanding of the tentative aspect of NOS and the roles of observation in scientific work, although they still showed some confusion regarding the distinction between observation and inference and the socio-cultural aspect of NOS. Interestingly, in another study, Akerson and Donnelly (2010) reported that young children (between kindergarten and second grade) participating in a Saturday science workshop tended to make connections among aspects of NOS, particularly regarding subjectivity, inference, and empirical aspects. The students realized that scientists viewed data from the perspective of their own backgrounds and aspirations. According to the authors, students make these connections when talking about observation and inference and about empirical data. The authors concluded that these results were evidence that the students "truly internaliz[ed] these ideas" and "were able to apply them in their everyday lives."

In another study with six grade students, Yacoubian and BouJaoude (2010) found that most of the 38 participants from a Lebanese school also held naïve views of subjectivity and the socio-cultural aspects of NOS (95 and 92%, respectively) at the beginning of the instructional intervention, while their views on other aspects of NOS were also naïve, but in lower proportions.

While looking for patterns among studies, it is important to consider that most of the research conducted in elementary schools usually assesses only a few aspects of NOS: the creative, empirical, provisional, inferential, and least frequently, subjective and socio-cultural aspects of NOS and the myth of "the scientific method." In contrast, the concept of the relationship between theory and law is usually not measured in elementary students. Therefore, caution should be used when comparing and analyzing results.

Table 1 Summary of studies about NOS understanding in elementary school students (K-6) analyzed

Authors	Duration (*n*)	Grades	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instrument
1. Khishfe and					Abd-El-Khalick (2002)	10 weeks (62)	Sixth grade	Content course	Int
C: 3 ➔ 34	Inquiry activities and reflection	The most naive was T and the most informed was C	The aspect that most improve was T and the lest improve were C and O&I	T: 6 ➔ 52 O&I: 9 ➔ 40 E: 6 ➔ 48	VNOS items				
2. Akerson and Volrich (2006)	13 weeks (14)	First grade	Content course	Non-Int and Int	reflexive activities	The most naive was T and the most informed was O & I.	The aspect that most improved was C and the lest improved was O&I	T: 14 ➔ 14 C: 12 ➔ 14 O: 14 ➔ 14	Interviewed using VNOS-D
3. Akerson and Donnelly (2010)	6 weeks (18)	K to second grade	Informal inquiry & NOS course	Non-int & int	Inquiry activities & reflection	The most naive was O&I and the most informed was E.	The aspect that most improved were C and O&I and the lest improved was S.	C: 17 ➔ 18 T: 14 ➔ 18 E: 12 ➔ 18 O&I: 17 ➔ 18 S: 9 ➔ 18	Conversations related VNOS-D
4. Quigley et al. (2010)	6 weeks (25)	K to	Informal inquiry &	Int	Inquiry activities & reflection	The most naive was S and the	The aspect that most improved was T and E and	Overall the students improved their understanding of the target aspects of NOS. There was still some confusion	Qualitative approach based on

Table 1 (continued)

Authors	Duration (*n*)	Grades	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instrument
		second grade	NOS course			most informed was E	the lest improved was S&C	regarding the distinction between observation and inference.	the VNOS-D
5. Yacoubian and BouJaoude (2010)	8 weeks (38)	Sixth grade	Inquiry course	Int	Inquiry activities & reflection	The most naive was S and the most informed was T	The aspect that most improve was E and the lest improve was T	T: 15 ➔ 15 E: 0 ➔ 45 S: 0 ➔ 25 Social: 0 ➔ 30	POSE
6. Akerson et al. (2014a)	1 year	Third grade	Content course	Int	reflexive activities	The most naive was S and the most informed was E	The aspect that most improve was S and the lest improve was T	O&I: 56 ➔ 63 E: 94 ➔ 94 S: 25 ➔ 39 T: 38 ➔ 50	VNOS-D2
7. Papadouris and Constantinou (2014)	5 weeks	Sixth grade	Content course	Int	HOS and inquiry-oriented activities engaging students in epistemic discourse	All naive views at the beginning	Most of students develop more sophisticated epistemology of C, E and O&I	Students became better positioned to recognize observations and interpretations and to differentiate between them, based on epistemological criteria	Interview
8. Fouad et al. (2015)	6 weeks (17) 4,5 h.	Second, third, and fourth grade	Content course	Non-int & int	Inquiry vs. HOS	The most naive was S and the most informed was C and T	The aspect that most improved was C and least improved were O&I and T	Changes in number of students at informed category (summary of four grades) Inquiry group E: 0 ➔ -1; T: 1 ➔ 0 C: 0 ➔ 1; S: 0 ➔ 1 O & I: 0 ➔ 1–2 History group E: 0 ➔ 1–1; T:(textbooks) 0 ➔ 0; T, C (dinosaurs) + 1 ➔ 1–1; S: 0 ➔ 0 O & I: (weather) 1/ ➔ -1	VNOS-D

Table 1 (continued)

Authors	Duration (*n*)	Grades	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instrument
9. Michel and Neumann (2016)		Sixth and seventh grade	Content course	Non-int & int	Generic NOS activities	The article did not show previous view of NOS	Five NOS aspects were studied (C, O&I, S, T, T&L).	Students did not change scores on the NOS instrument. But a more adequate NOS view was relating to students' understand of nature of energy.	NOSSI and VNOS-C

NOS aspects are as follows: T = tentativeness, O&I = observation and inference, S = subjectivity, C = creativity and imagination, E = empirical based, S&C = socially and culturally embedded; Int = integrated activities; Exp = explicit; and Imp = implicit. Data at results column correspond to % of students in informed category before and after intervention

Table 2 Summary of studies about NOS understanding in secondary school students analyzed

Authors	Duration (*n*)	Grade	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instrument
1. Liu and Lederman (2002)	1 week (29)	Seventh	Science camp	Non-Int and Int	Black box activities/inquiry activities	The most naive were S&C and C	The aspect that most improved was C and the least improved were T, S, S&C	Before the intervention most of students have basic view of NOS. The changes are not significant	VNOS-C
2. Khishfe and Lederman (2006)	6 weeks (42)	Ninth	Content course	Non-Int and Int	Inquiry activities & reflection	The most naive was E and the most informed was C	The aspect that most improved was O&I and the least improved was T	E: 0 ➔ 55 T: 0 ➔ 33 S: 24 ➔ 72 O&I: 5 ➔ 67 C:10 ➔ 60	VNOS-D
3. Khishfe and Lederman (2007)	7 weeks (139)	Ninth to eleventh	Content course	Non-Int and Int	Inquiry activities & reflection	The most naive were S and T and the most informed was O&I	The aspect that most improved were S and O&I and the least improved was T	The aspects S, O&I, E, T, and C increased between 30 and 60% for both treatments.	
4. Kim and Irving (2009)	7 weeks (33)	Tenth	Content course of genetics	Int (highly contextualized)	HOS activities	The most naive was T&L and the most informed was T	The aspect that most improved was E and the least improved was T	E: 0 ➔ 23 T: 67 ➔ 69 S: 20 ➔ 38 O&I: 20 ➔ 31 C:7 ➔ 23 S&C: 13 ➔ 31 T&L:7 ➔ 23	VNOS-C
5. Peters and Kitsantas (2010)	4 weeks (83)	Eighth	Content course	Int	Metacognition activities	VNOS-B was used, but Only general results are showed.	There exists a statistically significant difference between the beginning and the	There is a significantly higher gain in content knowledge and NOS knowledge for the experimental group	VNOS-B

Table 2 (continued)

Authors	Duration (*n*)	Grade	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instrument
							end of the view of NOS.		
6. Khishfe (2012)	4 weeks (88)	Ninth	Content course genetics	Non-Int and Int (highly contextual-ized)	SSI activities & reflexion	The most naive was T and the most informed was E	The aspect that most improved was E and the least improved was T	E: 12 ➔ 58 T: 5 ➔ 24 S: 24 ➔ 68 O&I: 22 ➔ 63 C:15 ➔ 41	Some questions from: VNOS- B and C
7. Peters (2012)	6 weeks (246)	Eighth	Content course of electricity and magnetism	Int	Hands on-inquiry lessons of con-tent including NOS	The most naive was T and the most informed was E	Most improved was E and least improve were T&L and T, but did not were teach.	There are significant differences between both groups for the 4 aspects of NOS explicitly addressed. (E, T&L, C and, habits of mind of scientists)	VNOS-B
8. Russell and Aydeni-z (2012)	1 semes-ter (63)	Ninth to Twelfth	Elective courses (microbiol-ogy)	Non-Int and Int	Inquiry activities, scientific research experience and online discussion	The most naive were SM, S&C, S, C, and the most informed was T	The aspect that most improved were O&I, S&C, C and the least improved were SM and T	E: 23 ➔ 100 T: 87 ➔ 97 S: 16 ➔ 90 O&I: N/A ➔ 90 S&C: 16 ➔ 97 C:16 ➔ 97 SM:13 ➔ 71 Col: N/A ➔ 96	VNOS-C
9. Khishfe (2014)	8 weeks (121)	Seventh	Content course (unit about the water usage and safety)	Int (highly contextual-ized)	argumentation and SSI activities	Naive for S, T, and E	The three aspects of NOS improved considerably	E: 13 ➔ 65 T: 8 ➔ 46 S: 13 ➔ 57	Controversial SSI Question-naire (CSI)
10. Khishfe (2015)	6 weeks (24)	Tenth	Content course of genetic engineering	Int	Case study, role play, debates, discussions and reflection	All three aspects very naive more than	The aspects that most improved were S and E and the least improved was T	Pre-Post-Delayed E: 19 ➔ 61 ➔ 40 T: 10 ➔ 46 ➔ 33 S: 19 ➔ 81 ➔ 46	(CSI)

Table 2 (continued)

Authors	Duration (*n*)	Grade	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instrument
11. Herman (2018)	7 days (60)	7th ($n = 23$), 8th ($n = 19$), 9th ($n = 13$), 10th ($n = 4$), 11th ($n = 1$) grades	Field work to Yellowstone National Park	Non-Int and Int	Documentaries, discussion, observation activities, readings, presentations, excursion and reflection socio-scientific and ecological engagement dimensions survey II (SEEDSII)	60% of student All aspects are naive	The aspects that most improved were ME, RST, SO and NOST, and the least improved was CPI	ME:2 ➔ 37 NOST: 0 ➔ 27 SO: 0 ➔ 30 RST: 0 ➔ 31 CE:0 ➔ 15 CNI: 6 ➔ 17 CPI: 2 ➔ 9 PE:0 ➔ 15	The

NOS aspects are as follows: T = tentativeness, O&I = observation and inference, S = subjectivity, C = creativity and imagination, E = empirical based, S&C = socially and culturally embedded, T&L = theory and law, SM = scientific method, Col = collaborative interaction, ME = methodology of environmental science investigations, NOST = nature of scientific theories, such as trophic cascade, SO = scientific observations of nature, RST = role of science and technology for solving environmental issues, CE = cultural influences on environmental science and its use, CNI = compassion toward nature impacted by contentious environmental issue, CPI = compassion toward people impacted by contentious environmental issues, PE = pro-environmental intent, Int = integrated activities, Exp = explicit and Imp = implicit, SSI = socio-scientific issues. Data at results column correspond to % of students in informed category before and after intervention

4.2 Understanding of NOS and Instructional Characteristics at the Secondary Level

In the 11 reviewed studies of secondary students' views of NOS, the most common intervention was content courses (eight studies), and most of them included either both integrated and non-integrated contexts (six studies) or only integrated activities (five studies). There was substantial diversity in teaching strategies, but the most commonly used was inquiry activities and reflection (five studies). A higher number of NOS aspects was included in secondary school studies compared with elementary school studies (18 aspects); the most frequently studied ones were the tentative, subjective, and empirical aspects of NOS (nine times) and observation and inference and creativity (seven times) (see Table 2). At the beginning of the studies, most students held naïve views about these NOS aspects, especially for the tentative (five studies) and the subjective (four studies) NOS. At the end of the interventions, the

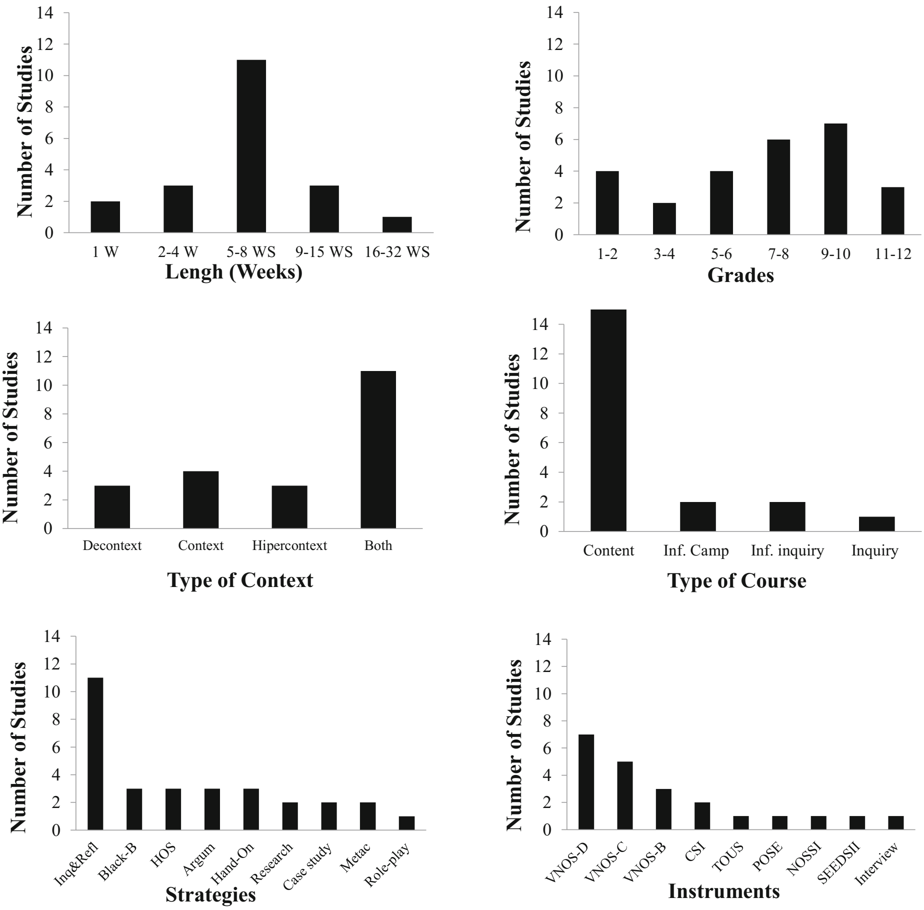

Fig. 2 Main characteristics of the analyzed studies at the school level (including elementary and secondary students). Graphs include length, grades, types of courses, types of context strategies used, and instruments applied

students' most improved area of understanding was the empirical NOS (four studies). Most interventions used the VNOS instrument to assess students' understandings of NOS (versions B, C, or D) (seven studies).

In terms of a more qualitative analysis, much work has been done by Khishfe (Khishfe 2012, 2014, 2015; Khishfe and Lederman 2006, 2007), especially regarding the issue of assessing the contribution of integrated or contextualized activities to the understanding of NOS and the effect of SSI as a curricular element that promotes a more sophisticated view of NOS. Specifically, in a very interesting paper, Khishfe (2015) studied the learning and retention of three NOS aspects among 24 tenth-grade students. Using two SSIs as a context (genetically modified food and water fluoridation) for teaching the tentative, subjective, and empirical aspects of NOS, the study showed that although some students returned to their previous naïve understandings 4 months after the end of the intervention, most participants held a more sophisticated view of NOS at the end of the intervention than they did at the beginning. Khishfe (2015) proposed that an important variable that could explain the regression of some students on the delayed test performed in the study was the short length of the intervention (6 weeks). This finding suggests that interventions likely need to be longer in order to enable students to experience multiple NOS instruction strategies.

In the same vein as the previous studies, it is interesting to highlight the work of Herman (2018), who evaluated the contribution of the socio-scientific context to NOS views of middle and secondary students (seventh to eleventh grades) in an informal teaching experience at Yellowstone National Park. Through the development of a new instrument associated with environmental education and ecological theory, the study showed a significant improvement in students' understandings of NOS aspects, such as the methodology of environmental science investigations, the nature of ecological theories, scientific observations and interpretations of nature, the role of science in solving environmental problems, and cultural influences on how environmental science is conducted. Even more remarkable is the fact that this study is one of the few that provides evidence of a real relationship between a more sophisticated view of NOS and better decisions made by students in socio-scientific contexts.

4.3 Summary of Students' Understanding of NOS and Instructional Characteristics

Based on the analysis of the 20 studies, we provide practical suggestions for future teaching and research efforts toward promoting elementary and secondary students' NOS views.

For science teachers, the primary message is that NOS instruction can be effectively accomplished with relative success at all levels from K-12. Moreover, one of the few variables that is clearly important is the length of the intervention (Fig. 2). At most levels, interventions lasting between 6 and 8 weeks appear to be the most common. Usually, in secondary schools, this duration allows the teaching of one or two science concept units in which NOS is embedded. In the same vein, it is clear that it is not easy to include courses or units devoted only to NOS, although in most countries, NOS is explicit in curricular documents (but see Olson [2018], for an analysis about "how" NOS is included). In terms of the frequency of intervention, the studies reviewed suggest that it is best to include both contextualized and decontextualized activities, the latter being easier to implement in special courses, such as informal inquiry courses.

Table 3 Summary of studies about NOS understanding in pre-service elementary teachers

Authors	Duration (*n*)	Course	Context	Strategies	Pretest views	Posttest views	Results	Instruments
1. Akerson et al. (2000)	1 semester (50)	Science methods course	Non-Int	Activities + reflection + reading	Most naïve aspect was T&L and most informed was S&C	Most improve were T, T&L and C and the least improve was S	E: 4 → 32 T: 8 → 72 C: 24 → 80 S: 32 → 52 S&C: 56 → 80 O&I: 40 → 80 T&L: 4 → 48	VNOS
2.				Abd-El-Khalick and Akerson (2004)	1 semester (28)	Science methods course	Non-Int	Activities-
+ reflection & reading papers	Most naïve aspects were T&L and T and the most informed was E	Most improve was C and the least improve was E	E: 29 → 71 T: 11 → 64 C: 18 → 86 S: 18 → 82 O&I: 25 → 75 T&L: 11 → 75 SM: 14 → 68	VNOS-B				
3. Akerson et al. (2006)	1 semester (19)	Science methods course	Int and non-Int	Reading, hands-on activities + reflection	Most naïve aspect was T&L and most informed was T	Most improve were T&L and C and the least improve was E	All aspects show improved views, but after 5 months, T, C, S, E, S&C and O&I reverted	VNOS-B
4. Matkins and Bell (2007)	1 semester, 13 h (15)	Science methods course	Int (highly contextualized) and non-Int	Activities + reflection & SSI elements	Most naïve aspects were T, C and S&C and most	Most improve was C and the least improve was S&C	E: 27 → 73 T: 0 → 60 C: 0 → 67 S: 20 → 80 S&C: 0 → 27	Views of science and global climate change

Table 3 (continued)

Authors	Duration (*n*)	Course	Context	Strategies	Pretest views	Posttest views	Results	Instruments
					informed was E			question-naire
5.				Abd-El-Khalick and Akerson (2009)	1 semester (25)	Science methods course	Non-Int	Activities-
+ reflection & metacognition. & hands-on activities	Most naïve aspects were T and O&I and most informed was E	Most improve were T and O&I and the least improve was S	E: 12 ➔ 68 T: 8 ➔ 72 S: 0 ➔ 48 O&I: 0 ➔ 64 C: 8 ➔ 56	VNOS-C				
6. McDonald (2010)	11 weeks (5)	Science content course	Int (highly contextualized)	Inquiry activities + SSI & HOS elements + argument	Most naïve aspect was T&L and most informed were O&I and T	Most improve was S and the least improve were O&I, E, T and S&C	Developed aspects in 4 or 5 participants: SM, S Unchanged aspects in 4 or 5 participants: T&L, T	VNOS-C
7. Bell et al. (2011)	1 semester (75)	Science methods course	Int (highly contextualized) and non-int	Activities + reflection vs. SSI elements	Most naïve aspect was T&L and most informed E	Most improve was T&L and the least improve was S	Best treatment: E: 17 ➔ 90 T: 6 ➔ 72 C: 11 ➔ 83 S: 17 ➔ 67 O&I: 6 ➔ 56 T&L: 0 ➔ 78 T: 0 ➔ 63	VNOS-B
			Int and non-int					VNOS-B

Table 3 (continued)

Authors	Duration (*n*)	Course	Context	Strategies	Pretest views	Posttest views	Results	Instruments
8. Akerson et al. (2012)	1 semester (17)	Science methods course		Reading + assignments + activities + reflections focus in cultural values	Most naïve aspect was T&L and most informed C	Most improve was O&I and the least improve was E	O&I: 0 ➔ 81 T&L: 0 ➔ 25 E: 13 ➔ 31 C: 19 ➔ 75 S: 13 ➔ 56 S&C: 13 ➔ 56	
9. Ozgelen et al. (2013)	1 semester (34)	Science lab course	Int and non-Int	Inquiry activities + reflection	Most naïve aspect was T&L and most informed C	Most improve was S and the least improve was T	E: 3 ➔ 18 O&I: 0 ➔ 18 T&L: 0 ➔ 29 S: 0 ➔ 44 T: 0 ➔ 12 C: 15 ➔ 79 S&C: 0 ➔ 24	VNOS-B

NOS aspects are as follows: T = tentativeness, O&I = observation and inference, S = subjectivity, C = creativity and imagination, E = empirical based, S&C = socially and culturally embedded, T&L = theory and law, SM = scientific method, Int = integrated activities, Exp = explicit, Imp = implicit. Data at results column correspond to % of teachers in informed category before and after intervention. Data at results column correspond to % teachers in informed category before and after intervention

Table 4 Summary of studies about NOS understanding in pre-service secondary teachers analyzed

Authors	Duration (*n*)	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instrument
1. Lin and Chen (2002)	1 semester (63)	SMC and history of science course	Int (highly contextualized)	HOS, group discussions, debates, demonstrations, hands-on experiments, readings	No creativity in science, scientist simply discover by good luck; explanations are based on intuition; theories are facts that have been repeatedly confirmed	Scientist may create different theories for a same phenomenon; explanations are based on scientific experiments; theories are tools for explaining natural phenomena	Experimental group understand better C, the theory-based nature of O&I, and the functions of theories	VOSTS (modified)
2. Schwartz et al. (2004)	10 weeks (13)	Internship in science course	Int	Real research experience & reflection	The most naive was T&L and the most informed was T	The aspect that most improved was S the least improved was SM	Number of students teachers in category: major change or enhanced E: 9; T: 8 S&C: 9 S:10; C: 9 T&L: 8 O&I:9 SM: 7	VNOS-C
3.		Abd-El-Khalick (2005)	2 years (56)	SMC and philosophy of science course	Non-Int	Generic explicit activities, readings, whole-class discussions, NOS-specific reflection papers, inquiry activities	The most naive were S and T&L and the most informed was S&C.	The aspect that most improved were T&L and E and the least improved were S

Table 4 (continued)

Authors	Duration (*n*)	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instrument
								and S&C.
POS course participants developed deeper and more coherent understandings of NOS compare with methods course participants	VNOS–C							
4. Lotter et al. (2009)	52 h distributed in 2 months (9)	Science methods course	Non-Int and Int	Explicit teaching, "practice" teaching experiences, readings, reflection papers	The most naive was S, and the most informed was SM	Both aspect improve in the same way	Positive changes in the pre-service teachers' views of NOS in terms of sophistication	VOSI
5. Seung et al. (2009)	2 semester, 12 h (10)	Science methods course	Non-Int & Int (highly contextual-ized)	Inquiry lab & reflection + HOS	The most naive were SM and E, and the most informed was S	The aspect that most improved was E and the least improved was C	E: 0 ➔ 7 O&I: 1 ➔ 7 SM: 0 ➔ 6 T: 4 ➔ 9 S: 8 ➔ 10 C: 0 ➔ 1 S&C: 5 ➔ 10	VNOS
6. Herman and Clough (2016)	3 years of a secondary science teacher education	Secondary science methods courses, nature of science and science	Non-Int & Int	Inquiry, questions regarding NOS	42% of the collective responses provided by participants on pre-NOS course	82% of the collective responses provided by participants on post-NOS course	NOS course positively impacted understanding of NOS. % of	VOSTS & SUSSI

Table 4 (continued)

Authors	Duration (*n*)	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instrument
	program with emphasis on NOS in 9 courses (13)	education course, restructuring science activities course			VOSTS items were informed	VOSTS items were in-formed.	informed collective responses: 42 ➔ 82	
7. Mesci and Schwartz (2017)	13 months (14 elementary and secondary science teachers)	NOS and science inquiry course	Non-Int and Int	Readings, concept map, laboratory activities, discussions	The most naive was T&L, and the most informed was O&I	The aspect that most improved were C and S, and the least improved was S&C	T: 0 ➔ 21.4 C: 0 ➔ 64.2 S: 0 ➔ 28.5 O&I: 0 ➔ 28.5 E: 0 ➔ 21.4 T&L: 0 ➔ 28.5 SM:14.2 ➔ 78.5 S&C: 0 ➔ 7.14	VNOS; VOSI & SUSSI

NOS aspects are: T = tentativeness, T&L = theory and law, NFT = nature and function of theories, O&I = observation and inference, S = subjectivity, C = creativity and imagination, E = empirical based, S&C = socially and culturally embedded, SM = scientific method, Int = integrated activities, Exp = explicit, Imp = implicit, SMC = science method course. Data at results column correspond to % teachers in informed category before and after intervention

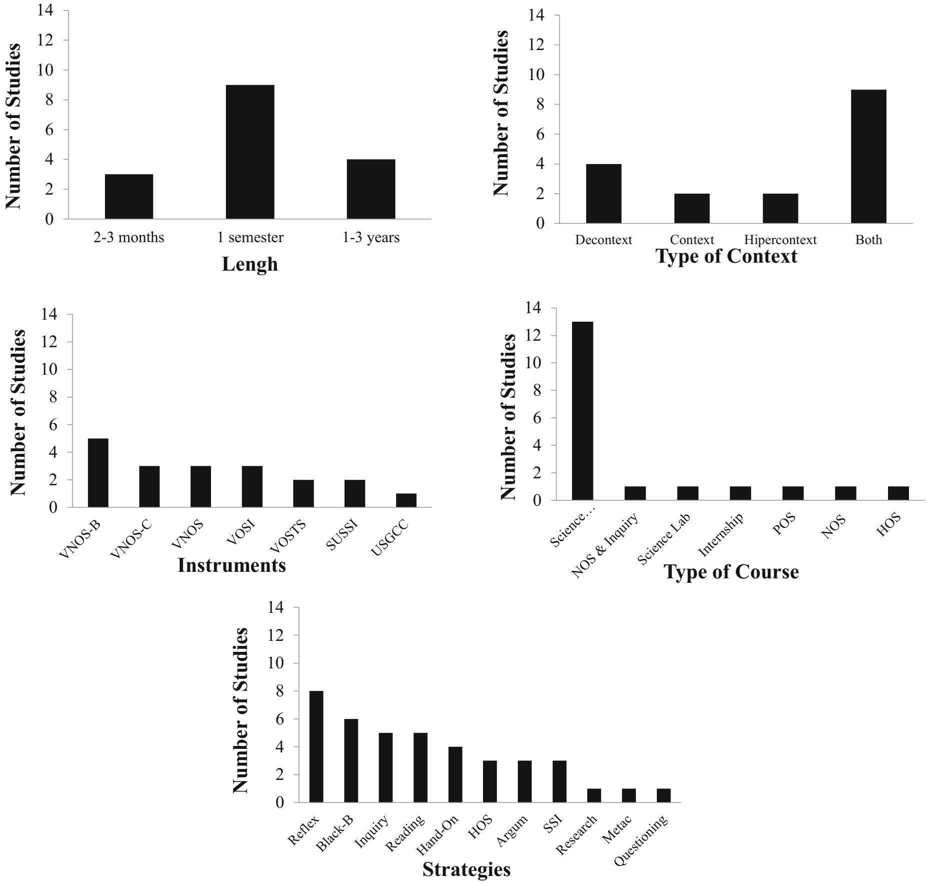

Fig. 3 Main characteristics of the analyzed studies at the pre-service level (including elementary and secondary science teachers). Graphs include length, grades, types of courses, types of context strategies used, and instruments applied

Regarding research, it is clear that more work is needed in informal contexts, or at least outside of regular science classes, and that longer interventions must be performed. Very few studies include students in the third and fourth grades and in the last years of secondary education (11th and 12th grades). Additionally, at least in the journals reviewed in this study, there are almost no longitudinal studies that allow the study of the development of NOS learning across several school levels. Such studies would make an important contribution to knowledge about NOS learning at the school level. Finally, although there is good evidence that the context of socio-scientific issues is a curricular element that is efficient for learning NOS, more teaching strategies should be used as study variables to determine whether any one strategy is more effective than others for teaching certain NOS aspects.

4.4 Understanding of NOS and Instructional Characteristics in Pre-service Elementary Teachers

Among the nine reviewed studies of pre-service elementary teachers' views of NOS, the most common intervention was science methods courses (eight studies), which usually lasted for a semester (eight studies). Many of the interventions included both integrated (even highly contextualized activities) and non-integrated contexts (five studies) or only non-integrated contexts (three studies). In most cases, the researchers included a variety of NOS teaching strategies, with hands-on activities with reflection and inquiry approaches as the most common (four studies), followed by the examination of socio-scientific issues (three studies). Most of the studies included the seven aspects used by the Lederman group (five studies), but a total of ten aspects were used among all of the studies, including "the scientific method" and collaborative interaction among scientists (Table 3). Most of the pre-service elementary teachers held naïve views about the relationship between theory and law at the beginning of the studies (seven studies), while their most informed views were about the empirical aspect of NOS. The aspects that improved the most were theory and law (four studies) and creativity (three studies).

In a more qualitative analysis of these works, we found that some described certain context conditions that could be related to their high effectiveness (Table 3). For example, Abd-El-Khalick and Akerson (2004) concluded that the achievement of notable effectiveness by the intervention was mediated by motivational, cognitive, and worldview factors. According to the authors, these factors were related to how pre-service teachers could internalize the importance and utility of teaching and learning NOS. The study also recognized the conceptual change teaching approach as one of the main factors explaining the results of the study, which was much more successful than previous research by the same group that did not have the same focus (Akerson et al. 2000). Other groups of researchers have tested other factors explaining success in teaching NOS. Bell and collaborators assessed socio-scientific issues as curricular elements that increased the effect of NOS learning (e.g., Matkins and Bell 2007; Bell et al. 2011). For example, in a very successful intervention, Matkins and Bell (2007) assessed the impact of situating explicit NOS instruction within a global climate change and global warming curriculum. The findings indicated that the participants' understandings of NOS within an SSI context greatly improved over the course of the semester and that pre-service teachers were able to apply their understanding to decision-making about socio-scientific issues. However, in a later work, Bell et al. (2011) showed that pre-service elementary teachers who experienced explicit instruction about NOS improved their views of NOS aspects, irrespective of whether instruction was situated within a socio-scientific context or was presented as a stand-alone topic. In other words, the patterns that we found when reviewing all studies demonstrate that there is not a clear relationship between teaching strategies and instructional effectiveness, similar to the findings of Bell et al. (2011): "Teaching nature of science without connecting it to a socio-scientific issue was just as effective as teaching it as an integrated component of global warming (SSI) instruction."

4.5 Understanding of NOS and Instructional Characteristics in Pre-service Secondary Teachers

Among the seven reviewed studies of pre-service secondary teachers' views of NOS, interventions took place within a very diverse group of courses, including NOS courses (two

Table 5 Summary of studies about NOS understanding in service elementary teachers analyzed

Authors	Duration (*n*)	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instruments
1.				Abd-El-Khalick (2001)	6 months (30)	Semester-long physics course.	Int	Reflex explicit NOS activitie-s, familiar, and
non-familiar content	The most naive were C, S, and T&L, and the most informed was O&I	The aspect most improved was O&I, and the least improved was S	% of stu-dents at naïve cate-gory. T&L: 40 ➔ 17 O&I: 30 ➔ 13 C: 67 ➔ 67 S: 63 ➔ 60	VNOS				
2. Akerson et al. (2007)	2 weeks (14)	Summer PDP, NOS, and inquiry course	Int and non--Int	Guided inquiry, reflex, activity	The most naive were E and O&I. The most informed was C	The aspect most improve was S&C, and the least improved were C	More informed answers in post workshop questionnaire	VNOS-D2
3. Akerson et al. (2009a)	2 weeks + 1 year follow-up (4)	Summer PDP	Int	Modeling, inquiry	The most naïve were S&C and			VNOS-D2

Table 5 (continued)

Authors	Duration (*n*)	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instruments
					T. The most informed was C	The most improve were S&C and O&I.	More informed answers in post-school year questionnaire	
4. Akerson et al. (2009b)	1 years (15)	PDP program	Int and non--Int	Guided inquiry, reflex, act, community of practice, action research focused on NOS assessment	The most naïve was S&C. The most informed was C.	The most improve were O&I, T, E, C, S&C	More informed answers after the summer workshop. Most advances lost after 1 year, excepting O&I	VNOS-D2
5. Morrison et al. (2009)	2 weeks (20)	Summer PDP with internship	Non-Int & Int	Act + reflex & reading p. & science internship, micro teach.	The most naïve was T&L, and the most informed was T.	The most improve was C and the least improved was T&L.	T: 5 ➔ 35 C: 0 ➔ 50 S: 5 ➔ 30 E: 5 ➔ 10 S&C: 0 ➔ 20 T&L: 0 ➔ 5 O&I: 0 ➔ 15	VNOS-B
6. Posnanski (2010)	2 years (22)	PDP	Non-int & Int	Act, readings, reflex, collaborative teaching design, action research	The most naïve were T&L and O&I the most informed were S, S&C	The most improve was C. The least improved were T&L and O&I	% by NOS aspects are not available, but average rubric scores change from 13,57 ➔ 17,20 after intervention	VNOS-C
7. Cofré et al. (2014)	1 year 60 h (12)	PDP, 2 NOS/SI course & 5 subject courses	Non-Int & Int	Act + inquiry lab with reflex.	The most naive were T, C, and O&I, and the most informed was E	The most improve was S. The least improve was E.	T: 0 ➔ 34 C: 0 ➔ 41 O&I: 0 ➔ 41 S: 9 ➔ 50 E: 83 ➔ 83	VNOS-D+
8. Deniz and Adibelli (2015)	12 weeks (4)	Graduate level course	Non-Int	Reading, hands-on active, reflex explicit NOS activities	The most naive were O&I, and the most informed were C, T, S	The most improve was O&I and the least improve was E	Number students in informed category E: 1 ➔ 1 O&I: 0 ➔ 1 C: 2 ➔ 4 S: 2 ➔ 4 T: 2 ➔ 3	VNOS-B
9.	Adibelli-Sahin	6 months (4)	PDP with	Non-Int	Reading, teaching materials	The most naive were O&I and		More

Table 5 (continued)

Authors	Duration (*n*)	Courses	Context	Strategies	Pre-test views	Post-test views	Results	Instruments
	and Deniz (2017)		two phas-es: NOS train-ing and NOS teac-hing			S&C, and the most informed was E.	The aspect most improved was E and the least improved were S	in-formed views after interven-tion, but not specific numeri-cal data
VNOS-D2								

NOS aspects are as follows: T = tentativeness, O&I = observation and inference, S = subjectivity, C = creativity and imagination, E = empirical based, S&C = socially and culturally embedded, SM = scientific method, Int = integrated activities, Exp = explicit, Imp = implicit, PDP = professional development program. Data at results column correspond to % teachers in informed category before and after intervention

Table 6 Summary of studies about NOS understanding in service secondary teachers analyzed

Authors	Duration (*n*)	Course	Context	Strategies	Pretest views	Post-test views	Results of effectiveness	Instrument
1. Nehm and Schonfeld (2007)	14 weeks (44)	Graduate biology course	Int	Exposure to misconceptions, collaborative learning, readings, videos	Focus in theory and law and its relationship with evolution. Evolution is weak because is a theory; theories become facts	Positive and significant increase in teacher knowledge of NOEVO	Statistically significant increase in teacher knowledge of NOS	Likert-type items and essay questions
2. Wong et al. (2008)	4 h (52)	Workshop	Int	Multimedia teaching materials, individual tasks, group discussion, and problem-solving activities	Most naive: "science influences political decisions" (0%) and "social and cultural practices" (0%), "scientists should not submit to authority" (0%), and "scientist are competitive by nature" (0%). Most informed: science is affected by social and cultural (56%)	All NOS aspects improved. Most improved: "science and technology impact each other" (65%). Least improved "science influences political decisions" (19%)	Increase (%) of participants showing good understanding of NOS & society: 34.6 scientist: 41.5.	VNOS-C (modified)
3. Niaz (2009)	11 weeks (17 second-ary and college level)	Graduate chemis-try educa-tion course	Int (highly contextual-ized)	HPOS readings, written reports, classroom discussions, presentations, written exams	Qualitative description of misconceptions, such as: universal scientific method; science is objective - sci-ence is experimental.	Qualitative description of change to: diverse methods; science is not absolutely objective, observations; and hypotheses are also important	Intervention facilitated the progressive transitions in teachers' understanding of SM, S, C and E	Question-answer sessions, written exams
4. Donnelly and Argyle (2011)	1 year (36)	TDP physics course	Non-Int & Int	Generic activities & hands one lab activities + reflection	Most naive was T&L, and most informed was E.	Most improve was T&L, and least improve was E	Number of teachers at least with adequate view at the end E: −2	VNOS-B

Table 6 (continued)

Authors	Duration (*n*)	Course	Context	Strategies	Pretest views	Post-test views	Results of effectiveness	Instrument
							I&O: + 10 S: + 9 T: + 2 T&L: 18 C: + 7	
5. Wahbeh and				Abd-El-Khalick (2014)	6 weeks, 36 h (19 middle and secondary level)	NOS PD course	Non-Int & Int (highly contextual-ized)	HPOS case studies, metacognitive strategies, lesson plans
Most naive were O&I and S, and most informed was E.	Most improve was T, and least improve was SM	Increase (%) of in-formed views: E: 31.6 I: 52.6 S: 68.4 T: 73.7 T&L: 31.6 SM: 5.3 C: 63.1 S&C: 52.7	VNOS-C					
6. Pavez et al. (2016)	120 h distrib-uted in 6 mont-hs (8)	Scientific skills and teach-ing	Non-Int & Int (highly contextual-ized)	Readings, HOS, videos, lesson plans, explicit instruction, hands-on active & reflection	Most naive was SM, and most informed were E and S.	Most improve was C, and least improve were T&L and S (eight aspects were studied)	After intervention the number of teachers who held informed views increased for	VNOS-D+

Table 6 (continued)

Authors	Duration (*n*)	Course	Context	Strategies	Pretest views	Post-test views	Results of effectiveness	Instrument
		evolution PDP					all of the aspects	
7. Cofré et al. (2017)	120 h distributed in 6 months (31)	NOS & evolution PDP	Non-Int & Int (highly contextualized)	Readings, HOS, videos, lesson plans, explicit instruction, hands-on active & reflection	Most naive were SM and T&L, and most informed was E.	Most improve was C, and the least improve was T&L	Informed views pre and post (%): E: 50 ➔ 87.5 O&I: 0 ➔ 50 T&L: 0 ➔ 25 C: 12.5 ➔ 87.5 S&C: 37.5 ➔ 87.5 SM: 12.5 ➔ 62.5 T: 0 ➔ 37.5 S: 50 ➔ 75	VNOS-D+

NOS aspects are as follows: T = tentativeness, T&L = theory and law, O&I = observation and inference, S = subjectivity, C = creativity and imagination, E = empirical based, S&C = socially and culturally embedded, SM = scientific method, Int = integrated activities, Exp = explicit, Imp = implicit. Data at results column correspond to % teachers in informed category before and after intervention

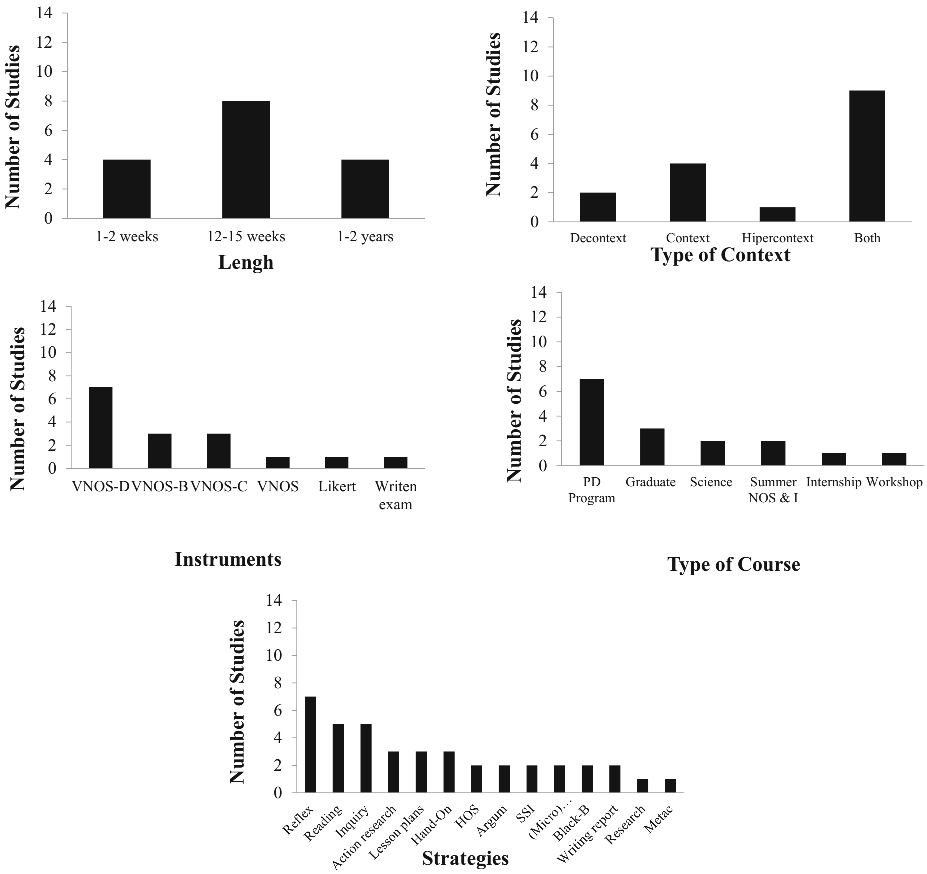

Fig. 4 Main characteristics of analyzed studies at the in-service level (including elementary and secondary science teachers). Graphs included length, grades, types of courses, types of context strategies used, and instruments applied

studies) and science methods courses (four studies) (Table 4). The interventions included mostly integrated and non-integrated contexts (four studies), and in most cases, the researchers included different instructional strategies, such as hands-on activities with reflexive discussions (three studies), readings (three studies), and the history of science (two studies). Most of the studies included the seven aspects proposed by the Lederman group and "the scientific method" (four studies). At the beginning of the studies, most pre-service secondary teachers held naïve understandings of theory and law (four studies). There was no clear pattern of improvement in NOS understanding after the interventions (Table 4).

In a more in-depth analysis of some of the studies, Lin and Chen (2002) showed that at the beginning of the interventions, some secondary teachers believed that there is no creativity in science and that scientists make discoveries based simply on good luck. Regarding theories and laws, some believed that there is a hierarchical relationship between theories and laws and that theories are guesses that cannot be tested or that certain facts can become theories after being repeatedly confirmed (Lin and Chen 2002). After the intervention, the pre-service teachers recognized the differences between theories and laws (Abd-El-Khalick 2005) and understood that the same phenomena may be explained by different theories (Lin and Chen 2002) and that theories may change over time (Abd-El-Khalick 2005).

On the other hand, some studies have suggested that some connections exist between the learning of different aspects by pre-service secondary science teachers (Schwartz et al. 2004; Seung et al. 2009). For example, in a study that included a science research internship course for pre-service secondary science teachers, Schwartz et al. (2004) found that most interns showed substantial developments in their NOS knowledge. The improvements recognized by the authors included science teachers' capacities for establishing connections among NOS aspects and between NOS aspects and science in a broader sense. For example, some pre-service teachers explained how tentativeness, observation, inference, and evidence connected to the setting and to science in general. Similarly, Mesci and Schwartz (2017) proposed that the conceptions of some aspects of NOS may be altered more easily than others. This study, which included 14 pre-service science teachers enrolled in an NOS and science inquiry course, indicated that most students initially held naïve views regarding most aspects of NOS, but their views changed after the course. However, several students still struggled with certain aspects, such as the differences between scientific theory and law, tentativeness, and socio-cultural embeddedness. These aspects are often "less likely to change," while the subjective, creative, empirical, and inferential NOS aspects are often "more likely to change" (see Fig. 5, in Mesci and Schwartz 2017). Interestingly, most of the aspects that change easily have also been described as the ones that are most connected to one another (Schwartz et al. 2004; Cofré et al. 2018). However, in one study with 56 secondary science teachers, Abd-El-Khalick (2005) reported a compartmentalization of knowledge among many participants. For instance, some participants noted that scientists use creativity in developing scientific knowledge and then ascertained that science is distinguished by the use of a universal "scientific method." This evidence of disconnection among understandings of NOS aspects seemed to disappear after additional instruction was delivered via the philosophy of science (POS) course. The 10 POS group participants seemed to have internalized informed views of almost all the target NOS aspects through making more connections among these aspects and supporting their arguments with adequate examples from the history of science discussed in the POS course.

Finally, an important result of Lotter et al. (2009) is the influence of cycles of practice teaching and guided reflections on pre-service teachers' views and enactments of NOS instruction. The authors focused on the types of support that pre-service teachers needed in order to transfer the learned practice models to actual class contexts. In addition to recording their views about NOS, the pre-service teachers summarized daily written reflections, which, through analysis with an instructor or collaborating teachers, allowed them to realize the relevance of their decisions during practice and to develop a more informed conception of their role as science teachers.

4.6 Summary of the Understanding of NOS and Instructional Characteristics in Pre-service Science Teachers

Based on our detailed analysis of the 16 studies of pre-service science teachers, we can say that, regarding science teacher education, it is important to note that a very diverse group of instructional characteristics were used in the interventions (Fig. 3). However, most studies shared some characteristics: a duration of at least one semester, the inclusion of NOS teaching in science methods courses, and the inclusion of both integrated and non-integrated contexts (Fig. 3).

Another pattern seems to be that some NOS aspects are more likely to change than others. According to Mesci and Schwartz (2017), NOS aspects of scientific theory and law, tentativeness, and socio-cultural embeddedness differ from other aspects because their understandings are more difficult to improve. This claim is partially supported by our review: according to our analysis, the aspects that showed the least improvement in understanding were the empirical, socio-culturally embedded, tentative, and subjective NOS. However, it is likely that our analysis has a small bias because in most cases, the understanding of the empirical aspect is the most informed at the beginning of interventions, so it is difficult to substantial increase this level of understanding by the end of the interventions; in addition, some of the studies did not include the aspect of theory and law at all.

In terms of research, more studies are needed on different types of courses (internships, HOS, or informal education), because the current research is focused almost exclusively on science methods courses. Additionally, future research could include comparisons of NOS learning between pre-service teachers who had different types of scientific knowledge before the intervention (earth sciences vs. biology or elementary teachers vs. secondary teachers) and could assess the effectiveness of the different strategies used.

4.7 Understanding of NOS and Instructional Characteristics in In-service Elementary Teachers

Among the nine in-service elementary teacher studies reviewed, the most common intervention model was a professional development program (PDP), which lasted for 1 or 3 years with or without a follow-up at the school (four). In all but one of the studies, 22 or fewer participants were considered, who had a wide range of years of experience in the classroom and previous science courses. Most of the interventions included both integrated and non-integrated activities (five studies), using a rather small number of strategies: hands-on activities followed by reflection (almost all of them) and readings and inquiry (in half of the studies). In most studies, the researchers recognized that teachers had the most naïve views on NOS aspects of observation and inference (five studies), theory and law (three studies), and socio-cultural embeddedness (three studies) at the beginning of the interventions. Teachers usually had the most informed view of creativity (four studies). Regarding the improvement of NOS aspects, the pattern is not clear, but the understanding of observation and inference (four studies) and of the socio-cultural embeddedness of science (three studies) were most frequently showed to increase. Teachers' understanding of the empirical aspect improved the least after intervention, but it is important to note that the teachers were sometimes already very informed of this characteristic at the beginning of the interventions (Table 5).

For a more qualitative analysis, two of the analyzed studies involved 2-year programs (Akerson et al. 2009b; Posnanski 2010) in which similar strategies, including peer collaboration, were used in the design of classes focused on NOS and the development of action research. Although both studies reported successful interventions, Posnanski (2010) reported less success than Akerson et al. (2009b), to the extent that teachers showed reversion in their understanding of NOS. Posnanski (2010) found that teachers' understanding of NOS were restricted to certain aspects and the understanding of some of aspects, such as theory and law, was less likely to change. Furthermore, Akerson and collaborators recognized the importance of an extended amount of time for allowing teachers to improve their NOS views, and they believed that the creation of a community of practice among teachers helped improve their views of NOS. In another long-term study and intervention, Cofré et al. (2014) found that understandings of the creative, inferential, and tentative aspects of NOS showed improvement after more than 1 year of work. Most teachers were already informed about the empirical aspect of NOS, and their understanding of the subjective aspect was particularly difficult to improve and was sometimes misunderstood to mean that any proposal from scientists could be valid. This work demonstrated that elementary teachers can learn NOS features in NOS courses as well as in content courses. This study did not use the most common course context, science method courses.

4.8 Understanding of NOS and Instructional Characteristics in In-service Secondary Teachers

Among the seven reviewed studies of secondary science teachers' views of NOS, the interventions took place over a diverse time period ranging from 4 h to 1 year (Table 6). The interventions included mostly integrated and non-integrated contexts, and in most cases (four studies), the researchers included different instructional strategies, with the history of science elements as the common setting (four studies). There was substantial diversity in NOS aspects included in the studies (Table 6), but the most frequently included ones were the seven aspects proposed by the Lederman group and "the scientific method" (four studies). Most secondary teachers held naïve views, such as that scientists use a universal scientific method based only on experiments at the beginning of the studies (four). Their views on the empirical aspect of NOS seemed to be the most informed (four studies). The NOS aspect that showed the greatest improvement in understanding was creativity (three studies); the understanding of theory and law improved the least (two studies).

For a more in-depth analysis, some very successful interventions show more qualitative aspects of teaching and learning NOS. For example, Wahbeh and Abd-El-Khalick (2014) studied 19 teachers who attended an intensive 6-week course on NOS and then taught NOS in their classes. The course was effective in helping teachers develop informed NOS conceptions and retain those understandings 5 months after its conclusion. The course included the seven aspects of the consensus view of NOS and the scientific method, and the only aspects for which fewer than 50% of participants held an informed view at the end of the intervention were theory and law and the scientific method. According to Wahbeh and Abd-El-Khalick (2014), some factors that could explain this success were embedding NOS instruction in the contexts of science content and the history and philosophy of science (HPS), metacognitive learning strategies, and a conceptual change framework.

In a different study (Niaz 2009), the author studied the transition of in-service teachers' NOS views throughout a course on the teaching of chemistry. This course focused on the HPS, and some controversial episodes were highlighted during the course. According to the data, the participants gradually developed more informed views on different aspects of NOS, such as the conception of the scientific method, objectivity in science, and the empirical nature of chemistry. The author attributed these transitions to opportunities for reflection and discussions of controversial historical episodes in chemistry.

In research developed by Wong et al. (2008), students were introduced to a perspective of authentic scientific practice through the development of case studies of contemporary scientific practice, beginning with a description of the response of the scientific community to the severe acute respiratory syndrome (SARS) epidemic in 2002–2003, as this response revealed many interesting aspects of NOS and authentic scientific research. The study, which included more than 60 pre-service and in-service science teachers, used interviews with key scientists involved in SARS research, together with analyses of media reports and documentaries produced during and after the SARS epidemic, as teaching strategies. The results showed that the learning context of the molecular biology of SARS was effective in promoting science teachers' understanding of NOS, mostly due to the relevance, familiarity, and personal experience of the history of science and the affective component of the interviews with the scientists. Improvements in understanding of NOS and scientific research were manifested in the realization of the inseparable links between science and the social, cultural, and political environment; in the deeper understanding of how science and technology impact each other; and in a deeper appreciation of the processes of authentic scientific research and the humanistic nature of scientists.

4.9 Summary of Understanding of NOS and Instructional Characteristics in In-service Science Teachers

Based on the analysis of the 16 studies of in-service elementary and secondary science teachers, we provide some practical suggestions for teaching NOS in science teacher development programs and advice for future studies on this topic.

Regarding science teacher development programs, it is important to note that almost all PDPs last for a year or involve summer workshops with more than 32 h of intensive work (Fig. 4). In terms of teaching variables, more PDPs tend to include different types of courses, not just science methods courses; they also include integrated and non-integrated activities, and the teaching strategies include not only hands-on activities and reflection but also a history of science element, microteaching experience, and even classroom monitoring of NOS instruction (Fig. 4). In terms of the difficulty of learning NOS aspects, although the scenario is complex, a recurring pattern suggests that certain subjects, such as understanding theories, socio-cultural aspects, subjectivity, and tentativeness, are the most difficult (Tables 5 and 6).

Regarding research opportunities in interventions with in-service science teachers, it would be beneficial to study the effectiveness of different teaching strategies and curricular elements, such as the history of science and socio-scientific issues, in more depth. Classroom planning and monitoring in classrooms should be studied not only to understand the determining factors for developing teachers' PCK for NOS (Wahbeh and Abd-El-Khalick 2014) but also to promote a better understanding of NOS aspects among science teachers.

5 Conclusions

More than 25 years ago, Lederman's classic review (Lederman 1992) concluded that both students and teachers had a poor understanding of NOS, that teachers' understanding could be improved by teaching explicitly and including the history of science, and that a more informed view of NOS is not a guarantee that teachers will be able to teach NOS in an effective way. Almost 10 years later, a widely cited review demonstrated that implicit teaching NOS through laboratory activities is a much less efficient approach than explicit and reflective teaching of NOS aspects (Abd-El-Khalick and Lederman 2000a).

In the current review of the characteristics of teaching NOS based on studies published over the past 18 years, we note that some patterns have emerged and practical advice can be provided for those who are interested in improving NOS understandings among students and teachers and determining the general populations' understanding of what scientific knowledge is and how this understanding is generated. Because most published and reviewed studies report successful interventions, we will make suggestions for teachers and science educators based on the identification of the intervention characteristics that were most frequently reported in this analysis.

5.1 For Which NOS Aspects Do Students and Teachers Hold the Most Naïve and the Most Informed Ideas at the Beginning of Teaching Interventions?

At the beginning of the interventions, the most understood NOS aspect was that science is based on empirical data. In at least 15 of the 52 studies reviewed, this aspect was the most understood among the participants. The next most understood aspect was creativity; participants were most informed on this aspect at the beginning of the intervention in six studies. A discussion of the least understood aspects of NOS at the beginning of the interventions is very difficult, because there was great diversity in the list of aspects included in the studies, with some lists including more than 20 aspects (see Tables 2 and 4 for examples). The lists of included aspects were shorter and more limited for elementary school students, more diverse for secondary students, and still more diverse in teachers' studies.

In terms of teaching, this diversity of aspects leads us to propose that teachers and science educators can teach at least a subset of aspects of NOS to elementary school students without major problems and that this teaching can focus on aspects other than the creative and empirical aspects of NOS. In addition, it shows us that those who want to teach NOS can use studies and activities applied to a range of aspects that goes far beyond the seven most frequently used aspects (Lederman 2007). However, many studies state that at the beginning of the intervention, most participants held uninformed views on all NOS aspects (e.g., Herman 2018). This finding tells us that in the incorporation of NOS into the curriculum and teacher training standards in the countries that focus research on NOS, teaching practices do not seem to have any effect on views of school students, pre-service, and in-service teachers. In fact, in a very recent analysis about the inclusion of NOS in the official documents of nine countries, Olson (2018) showed that NOS ideas are rarely included as expectations for student learning (only in Australia). If we add to this scenario that NOS is still notably absent from most science teacher education throughout the world (e.g., Olson et al. 2015; Cofré et al. 2015), it is reasonable to suggest that students and science teachers still do not understand the characteristics of scientific knowledge.

5.2 Which Ideas About NOS Held by Students and Teachers Offer the Most Opportunities for Improvement and Which Improve the Least After an NOS Instructional Intervention?

According to the literature review, the easiest aspects to learn were usually the empirical aspect, the difference between observation and inference, and the contribution of creativity to science, which were observed in participants ranging from kindergarten students to in-service teachers; participants were usually more informed on these aspects at the beginning of the interventions. The subjective (guided by theory) NOS and the generation of scientific knowledge by more than one method seemed to be somewhat more complex attributes that could sometimes be learned more easily than others (8 and 2 times, respectively), but sometimes showed the least improvement in understanding (9 and 3 times, respectively). Finally, the changing nature of scientific knowledge (tentativeness), the interactions of science with social and cultural aspects, and the nature of theories, laws, and models were more difficult to understand. These results are similar to the proposal made by Mesci and Schwartz (2017) in their work with pre-service science teachers. In their work, the authors proposed that understanding of some aspects is more likely to change, while the understanding of other aspects is less likely to improve.

These results allow us to propose that teachers and science educators should make greater teaching efforts or should be more careful with certain aspects of teaching NOS than others. In terms of research, several interesting topic questions arise: What is the true complexity of understanding the aspects of subjectivity and the multiple methods used to generate scientific knowledge? Are these aspects easy to learn, or is it difficult to change an individual's understanding of them? Does the educational level or the teaching strategy have any effects on the results of this teaching? The hypothesis of Mesci and Schwartz (2017) about two types of NOS aspects (more likely to change vs. less likely to change) could mean that we can recognize different levels of complexity in NOS aspects, similar to integrated and basic scientific skills.

5.3 What Is the Optimal Duration of an NOS Instructional Intervention for Students and Teachers?

According to our literature review, time or effort could be an important variable. Not much diversity was present in the duration of the interventions for each student and teacher group, and the researchers seemed to try to provide the longest possible intervention within the context of each educational level. For students, the most frequent duration was between 5 and 8 weeks; for pre-service teachers, it was one semester; and for in-service teachers, it was one year (or an intensive summer course of more than 32 h). Of course, in discussing time or duration, we are also referring to the intensity or effort involved in NOS intervention. Thus, a week-long intensive NOS intervention that lasts 30 h and an intervention that addresses NOS once a week for 3 h over 10 weeks should involve the same amount of intensity and effort. However, as Khishfe (2015) proposed, an important variable that could explain the regression that students demonstrated on delayed tests in some studies is the short length of the interventions available at secondary schools, which means fewer opportunities to learn about NOS.

5.4 What Are the Characteristics of NOS Instruction in Terms of the Courses, Context, and Strategies Used?

Our analysis revealed that a great diversity of courses, contexts, and strategies are used in teaching NOS; however, some patterns emerge regarding the frequency with which some of these courses, contexts, and strategies are reported. For example, the studies of students, pre-service teachers, and in-service science teachers most often used contexts that included not only activities with scientific content but also activities without "science." In fact, 29 out of 53 studies included both types of activities. This finding coincides with the opinions of some science teachers, who recognize the value of both types of context (Pavez et al. 2016; Cofré et al. 2018). Other researchers have shown that teachers with high NOS implementation incorporated both decontextualized and contextualized activities, whereas teachers with low NOS implementation limited their NOS instruction to isolated, decontextualized instruction (Clough and Olson 2012).

Regarding the type of courses, it is clear that for students, the preferred approach was to include NOS teaching associated with some scientific content of the curricula of each place where the study was carried out, while in the studies of pre-service teachers, NOS instruction was mainly provided in science methods courses. While these data may be helpful for future successful implementations at schools and universities, in terms of research, there is a need to explore other scenarios for teaching NOS; for example, more work on informal contexts, or at least those outside of normal science classes, for students is needed (see Herman 2018 for example) and teachers.

Finally, in relation to teaching strategies, our analysis shows that in the three levels analyzed (students, pre-service teachers, and in-service teachers), there is a great diversity of methodologies (see Figs. 3 and 4). However, some strategies, such as inquiry, practical activities combined with reflection, black box activities, and some content, such as SSI and the history of science, seem to be used more often. Because interventions with in-service science teachers include more opportunities for teachers to apply what they have learned (lesson plans, microteaching, follow-up teaching at schools), it is important to include more of these types of activities in pre-service science teacher NOS training. Perhaps this could be possible if more courses focusing only on NOS could be implemented in science teacher education (Olson et al. 2015; Cofré et al. 2015).

5.5 What Are the Most Effective Strategies for Teaching NOS to Students and Teachers?

While this was the most important and most interesting question to address in this review, after conducting the analysis, we understood that we did not have enough empirical evidence to infer a clear pattern. The lack of sufficient empirical evidence occurred not only because are there many variables that we were not able to include or control in this characterization (e.g., the teacher's performance while teaching NOS, the number of aspects taught in each intervention, and the extent of the intervention) but also because there is substantial diversity in the strategies and elements included in the teaching of NOS. In general, the studies did not describe "how" NOS content was taught; rather, they often just described the activities or topics covered. One of the few elements that was identified as a facilitator of the understanding of NOS was the use of socio-scientific issues. Whether the interventions applied a consensus approach that included the most-used aspects (Lederman's aspects) (e.g., Bell et al. 2011; Khishfe 2012, 2014, 2015) or an alternative approach that evaluated the aspects of NOS that are most contextualized in the discipline (e.g., Wong et al. 2008; Herman 2018), the results have been equally satisfactory. To answer this question, more comparative studies that assess the two strategies or elements are needed.

5.6 General Suggestions for Future Research

In this literature review on teaching and understanding NOS among students and teachers, we aimed to summarize the information available in mainstream journals. Based on this work and knowing that there are many limitations associated with the decisions we have made in carrying it out (for example, not reviewing aspects of the teachers' NOS PCK), we believe that it is possible to identify some new avenues for research on this topic:

1) Although it was not a goal of this investigation, our review identified only a few studies (no more than seven) that focused on aspects of NOS that differed from those most often used by authors who support the "consensus view." This finding shows that more empirical research is needed to evaluate the different theoretical approaches that have been proposed, such as the family resemblance approach (Irzik and Nola 2011), and the different concerns and criticisms regarding the consensus view. For example, is it possible to compare the effectiveness of these two approaches for investigating understanding of NOS in school students? Is the alternative approach more efficient for improving teachers' views than students' views?
2) Longitudinal studies of students are scarce, whereas longitudinal studies of science teachers are somewhat more common. Some longitudinal studies have shown a regression in participants' understanding of NOS. More studies of this type are needed to elucidate the efficiency of teaching strategies, which are the practices that allow learning to be sustained over time. Longitudinal studies could also answer questions about the connections among the understanding of different aspects and their degree of difficulty over the years. Some questions that are especially relevant in terms of the school curriculum should be investigated in future studies: What is the minimum presence of NOS in a national curriculum that is necessary for students to develop an informed view of NOS that persists over time? How many times should instruction on an aspect of NOS be included in different grades in K-12 curricula?
3) There does not seem to be a minimum depth of scientific content that promotes an understanding of NOS or the development of more informed views. If such a depth existed, then interventions would be less successful in groups with a lower conceptual background in science for both students (e.g., elementary students vs. secondary students) and teachers (e.g., elementary teachers vs. secondary teachers). Is knowledge of the discipline truly a factor that affects understanding of NOS? Quantitative studies with an experimental design or qualitative research with a case study design could help to answer this question.
4) Although there is a great diversity of aspects of NOS that can be studied, current evidence suggests that some aspects are more difficult to understand than others. More research can be conducted on this topic to try to answer questions such as "Are there aspects of NOS that should be learned or understood before others to ensure the development of a holistic view of how science works?" and "What is the most efficient learning progression of NOS aspects for students and teachers?"
5) There are a few examples of studies on teaching NOS in informal environments for students and teachers; therefore, more studies including these types of strategies should be carried out. In addition, the diversity of strategies used should allow more studies to be conducted in order to evaluate the effectiveness of different strategies for understanding different aspects of NOS. For example, are the roles of observations and inferences better learned in contexts of inquiry and laboratory activities or by reviewing and discussing historical episodes? There are still very few works that compare the effectiveness of two different teaching strategies, for example, inquiry vs. the history of science (Fouad et al. 2015), or studies that compare two different types of content, such as science content vs. SSI (Bell et al. 2011).

In summary, although the current context of the field of NOS might not seem very auspicious (e.g., recently, its scarce representation in the curricula of several countries has been discussed (Olson 2018) and thorough criticisms of the way most of the research has been carried out in the last 30 years have been made (see Schwartz et al. 2012; Kampourakis 2016 for response to these criticisms), this review offers a positive perspective for the future. There is strong evidence that it is possible to teach NOS to individuals ranging from the youngest students to the most experienced teachers; however, there are still many questions that must be answered with more and better research. These are unequivocal signals that the field of NOS is advancing and developing to make an important contribution to science education.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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