The Nature of Science and Citizenship: a Delphi Analysis

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Abstract

The relationship between science and society has, for many years, been the subject of debate in different fields, and various proposals have been made regarding the kind of science education that citizens require. The present study considers an understanding of the nature of science (NOS) to be one of the key competences that citizens should acquire as part of their science education. Hence, our aim was to identify NOS aspects among the key scientific competences for citizenship identified by a panel of Spanish experts. The analysis is based on a review of the recent literature on the NOS, and especially on the results of a previous Delphi study in which 31 experts were asked to propose key aspects of scientific competence for citizenship. The present study involved three stages: identification of NOS themes in the experts' initial proposals, analysis of how their importance ratings of these themes changed over the course of the Delphi rounds, and analysis of variability among the experts according to their professional group. We identified 12 NOS themes that, in line with recent publications in this field, included those related to the practice of science. A stable consensus was only observed for one theme: critical attitude. These results provide further evidence of the well-documented difficulty of defining and selecting NOS themes. However, the analysis also suggests that critical attitude is one of the key themes that should form part of science education for citizens.

Keywords: Nature of science (NOS), Scientific competence. Delphi study. Citizenship.

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Introduction

Over the last decade or so, an increasing number of critiques and proposals have emerged from the fields of social science research, enterprise, politics, and citizenship regarding the relationship between science and society. For instance, Irwin argues that the task for science and technology studies (STS) is to explore the shifting representations of scientific governance and to elucidate their core assumptions about both expertise and citizenship (Irwin 2006, p. 304). Similarly, the European Commission (2008) has highlighted the need for a renewed social contract for science, while Bensaude-Vincent (2014) notes that some authors already speak of a new social contract between science and society, one in which science is meant to respond to people's concerns and social demands—as opposed to the old model in which scientists were granted autonomy and public support, while the public, in return, were regarded as the passive beneficiaries of scientific and technological advancement. For their part, Smith et al. argue that Accounts of how scientists, as people, see their role in building relationships between science and society are broadly absent from the science education literature, and from school science curricula and policy documents (Smith et al. 2018, p. 3).

In this context, the relationship between science and society has increasingly come to be considered in terms of the degree of public participation and the flow of information (Haywood and Besley 2014; Pieczka and Escobar 2013). Toward the end of the last century, for instance, and with the aim of expanding science education and achieving greater acceptance of scientific investigation (SI) (Haywood and Besley 2014), much attention focused on what was referred to as the public understanding of science (PUS) (Bickerstaff et al. 2010; Michel 2012; Ryan 2015), a model in which scientists are regarded as bearers of knowledge and Blay citizens as the recipients of a scientific education. This is also known as the deficit model (Aitken et al. 2016; Irwin 2014; Jenkins 1994; Stockmayer and Bryant 2012; Sturgis 2014) because it defines the public as those-who-do-not-know (Bensaude-Vincent 2014). Recently, this type of relationship has begun to be replaced by what is regarded as a more democratic model, namely public engagement of science (PES) (Bauer 2014; Michel 2012; Ryan 2015; Sturgis 2014). According to Bauer (2014), the of in PES refers both to the modern public's engagement with science (objective genitive) and to the engagement of science with the public (subjective genitive) through public participation in science and technology. Although this is now the dominant model, not all authors interpret or apply PES in the same way, nor are they necessarily convinced that its objectives have been achieved (Bauer 2014; Haywood and Besley 2014; Irwin 2006; Nowotny 2014; Stilgoe et al. 2014; Sturgis 2014). Irwin (2006), for instance, suggests that public engagement is minor and limited in comparison with the large number of scientific committees and institutional processes that are yet to take on board new approaches to the governance of science. For her part, Nowotny (2014) highlights the limited involvement of the public and notes that while we tacitly believe that public engagement is about linking science to politics, our explicit knowledge of politics shows us that PES remains marginal to our concerns.

Given this situation, and the fact that science is increasingly present in our everyday lives, it is important to consider what kind of science education citizens need, and where and how they should acquire it. Answers to these questions have been proposed from different perspectives. Within the framework of Bcitizen science, Price and Lee (2013) suggest that since people spend most of their lives outside the formal school setting, citizen science projects could be used to promote informal science education. The question of where learning takes place has also been addressed by economists such as Stiglitz and Greenwald, who state that […] we can think of our lifelong education system as consisting of two parts, a formal part (schools) and an informal part (jobs and elsewhere). The two are complementary as much as substitutes: if the first does its job well, it increases the returns to expenditures by the second (Stiglitz and Greenwald 2016, p. 99).

From our perspective as researchers, we are interested in what science can contribute to citizen literacy, in the sense of helping people to participate effectively in all areas of their lives. As Driver et al. argue, Ban understanding of science content requires an understanding of the nature of science (Driver et al. 1996, p. 15), and hence, our aim here is to analyze the contribution which aspects related to the nature of science (NOS) can make to overall scientific literacy. There are three main reasons for this:

(a) The NOS is regarded as an essential aspect of formal science education. In recent years, numerous studies have highlighted the importance of teaching students about the NOS (Allchin et al. 2014; Berland and Crucet 2016; Deniz and Adibelli 2015; Herman et al. 2017; van Dijk 2014), and this has been accompanied by various proposals for curricular reform. Notable examples include Project 2061: Science for All Americans (American Association for the Advancement of Science (AAAS) 1989), Beyond 2000: Science education for the future (Millar and Osborne 1998) or, more recently, the Next Generation Science Standards (NGSS Lead States 2013, Appendix H), in which the NOS and SI form part of the dimensions crosscutting concept and scientific and engineering practices, respectively (Bartos and Lederman 2014).
(b) Research in this field shows that the NOS is one of the issues that provokes the most debate. In particular, consensus is lacking as to which aspects should be considered as representing the NOS and how they might be chosen (Allchin 2011; Abd-El-Khalick 2012; Schwartz et al. 2012; Erduran and Dagher 2014; Martins 2016; Herman et al. 2017; Kampourakis 2016; Mesci and Schwartz 2017). In a previous Delphi study conducted by our group (Blanco-López et al. 2015), in which we surveyed a panel of 31 experts from different science-related fields, we likewise noted the lack of agreement regarding certain aspects of the NOS.
(c) Despite the importance ascribed to it, the NOS has rarely been the main focus of interest in research on science education for citizens.

In light of the above, the present study considers an understanding of the NOS to be one of the key competences (Bybee 1997; DeBoer 2011; Fensham 2007, 2009, 2011; OECD 2002, 2006) that citizens should acquire as part of their science education. Accordingly, our aim was to identify NOS aspects among the key scientific competences for citizenship identified by a panel of Spanish experts. To this end, we begin by reviewing the recent literature that has reconsidered the notion of the NOS and the meanings ascribed to it. We then conduct a new analysis of the data and results obtained in our aforementioned Delphi study (Blanco-López et al. 2015) in order to offer a fresh interpretation of the findings.

Theoretical Framework

We have already noted that although the NOS is increasingly considered to be an important aspect of science education (NGSS Lead States 2013), there is no consensus as to what it entails or how its key elements might be identified. In this context, and faced with the lack of agreement over which ideas-about-science should be included in the contemporary school science curriculum, Osborne et al. (2003) carried out an empirical Delphi study to determine the degree of agreement on this issue among a panel of experts comprising scientists, science communicators, philosophers and sociologists of science, and science educators. Their analysis showed consensus regarding the following nine themes: scientific method and critical testing, creativity, historical development of scientific knowledge, science and questioning, diversity of scientific thinking, analysis and interpretation of data, science and certainty, hypothesis and prediction, and cooperation and collaboration.

When considering studies on the NOS, however, it is important to consider whether these studies refer to the same concept (Schizas et al. 2016). A review of the literature suggests that this is not the case. For instance, in the context of formal science education, what is referred to as the domain-general approach, or consensus view (Abd-El-Khalick 2012), tends to predominate. However, this approach has been widely criticized in recent years, notably for offering a too restrictive view of the NOS, and as a result, a number of alternative perspectives have been proposed. Lederman et al. (2002), noting the way in which the NOS was often conflated with scientific processes, stated the following: we consider scientific processes to be activities related to the collection and interpretation of data, and the derivation of conclusions. NOS, by comparison, is concerned with the values and epistemological assumptions underlying these activities (Lederman et al. 2002, p. 499). As regards the distinction between the NOS and SI, Bartos and Lederman (2014) consider the NOS to be limited to the characteristics of scientific knowledge that derive from the way in which it is created, that is, through SI, with the latter being defined by Lederman et al. (2014) as the processes of how scientists do their work and how the resulting scientific knowledge is generated and accepted (Lederman et al. 2014, p. 66). Another interpretation of this approach is to consider only those aspects common to all the sciences (Schwartz and Lederman 2008). More specifically, Bartos and Lederman consider the following to be tenets that exemplify the NOS: (1) scientific knowledge is empirically based; (2) observations and inferences are qualitatively distinct, in that the former are directly accessible to the senses while the latter is only identified through its manifestation or effects; (3) scientific theories and scientific laws are different types of knowledge; (4) the generation of scientific knowledge requires, and is a partly a product of, human imagination and creativity, from generating questions to inventing explanations; (5) scientific knowledge is theory-laden (i.e., influenced by scientists' prior knowledge, beliefs, training, expectations, etc.); (6) scientific knowledge both affects and is affected by the society and culture in which it is embedded; and (7) scientific knowledge, while reliable and durable, changes (Bartos and Lederman 2014, p. 1153). Some researchers have based their studies on lists of general NOS aspects similar to those listed above. A further point to consider, as noted by Kampourakis (2016), is that independent proposals of general NOS aspects share crucial similarities, and this has led to the conclusion that there is a consensus among science educators on this topic. For this reason, this way of conceptualizing NOS has been described as the Bconsensus view of NOS (Kampourakis 2016, p. 669). Finally, it should be noted that the seven aspects listed above provide the framework for the Views of Nature of Science Questionnaire (Lederman et al. 2002), which according to Hodson and Wong (2014) is probably the most widely used instrument for assessing the views of students of different ages, and teachers, regarding the NOS.

As already mentioned, the consensus view has come in for criticism in recent years, and a number of alternative and broader perspectives on the NOS have been put forward, giving rise to much debate. For instance, both Wong and Hodson (2009) and Hodson and Wong (2014) draw attention to the actual practice of scientists and seek, in their words, to reinforce, extend, enrich, qualify and modify the consensus view with the perspectives of practising scientists and with illustrative examples from the contemporary practice of science (Hodson and Wong 2014, p. 2640). These authors, who Abd-El-Khalick (2012) regards as proponents of what he calls the domain-specific approach, consider that the definition of the NOS should not be limited to the characteristics of scientific knowledge (i.e., to epistemological considerations). They argue that excluding consideration of the nature of scientific inquiry might strike some as an odd decision, given that much of our scientific knowledge and, therefore, consideration of its status, validity and reliability are intimately bound up with the design, conduct and reporting of scientific investigations. Moreover, teaching activities focused on NOS often include empirical investigations and/or critical scrutiny of existing data. [. . .] In short, the processes and the products of scientific inquiry are inextricably linked (Hodson and Wong 2014, p. 2642). Having offered this criticism, they go on to propose a definition of the NOS that encompasses the following aspects: the characteristics of scientific inquiry, the role and status of the scientific knowledge it generates, the modelling that attends the construction of scientific theories, the social and intellectual circumstances of their development, how scientists work as a social group, the linguistic conventions for reporting, scrutinising and validating knowledge claims and the ways in which science impacts and is impacted by the social context in which it is located (Hodson and Wong 2014, p. 2642). Other authors go further and argue for the inclusion of aspects derived from the science, technology, society, and environment (STSE) framework, which has contributed considerably both to research on science education and to scientific literacy (Acevedo and García-Carmona 2016; Duschl et al. 2006; Vázquez-Alonso et al. 2013). An even broader perspective has been proposed by García-Carmona and Acevedo-Díaz (2017), who consider NOS as comprising four dimensions: (1) epistemology of science, (2) relationship between science and technology, (3) internal sociology of science, and (4) external sociology of science.

The philosophers of science Irzik and Nola (2011) have also criticized the domain-general approach and propose an alternative known as the family resemblance approach (FRA). They argue that this approach to the NOS overcomes the weaknesses and limitations of the consensus view, since it is both more comprehensive and better able to capture the open and dynamic nature of science. The FRA conceptualizes science as being both a cognitive– epistemic system and a social–institutional system. The former comprises processes of inquiry, aims and values, methods and methodological rules, and scientific knowledge, while the latter consists of professional activities, scientific ethos, social certification and dissemination of scientific knowledge, social values, social organizations and interactions, political power structures, and financial systems. Erduran and Dagher (2014) drew upon the FRA of Irzik and Nola (2011) with the aim of characterizing the NOS in science education. Their revised model incorporates a set of practices, methodologies, objectives and values, and social norms and gathers together aspects of the NOS from different approaches. According to these authors the ‘family resemblance’ theme provides a much needed coherence to how we can envisage science from a more holistic perspective (Erduran and Dagher 2014, p. 25).

Kampourakis (2016) considers the criticisms made by various authors of the domain general approach and summarizes them into four important limitations: (1) Science cannot be adequately described by lists of simple statements, such as those in the general aspects conceptualization of NOS. (2) The general NOS aspects are aspects of human knowledge in general and not of science in particular; therefore, they should not be presented as characteristics of science. (3) There are no aspects or methods that are common across all science, and so the general aspects conceptualization of NOS is blind to important context-specific features of the various science disciplines, as well as to the differences among them. (4) The aspects of the inquiry processes of science are either not included in the lists of general NOS aspects, or when they are included they are distinct from the epistemological aspects. (Kampourakis 2016, p. 674).

In the same article, however, Kampourakis (2016) responds to these criticisms of the domain-general approach as follows: (1) Whatever is taught at schools has previously undergone some kind of didactic transposition (not just simplification) in order to align with the pedagogical goals. (2) The main aim of the general NOS aspects conceptualization is to address students’ preconceptions about NOS by discussing some aspects common across all science, not to give them criteria for demarcating science from non-science. (3) It seems unclear how (2) can be achieved if NOS instruction begins from the specifics of the various science disciplines and their differences, instead of general aspects that can then be elaborated upon with reference to specific disciplines. (4) It seems pedagogically useful to distinguish between aspects of NOS and aspects of SI because students have been found to conceptualize them independently. (Kampourakis 2016, p. 676).

Despite, or perhaps owing to, the controversy, proponents of the consensus view have put forward teaching proposals in which the domain-general approach is complemented with some of the ideas discussed by its critics (Abd-El-Khalick 2012; Kampourakis 2016).

In terms of the ideas-about-science that the general public should ideally assimilate, Osborne et al. (2003) argued that in order to engage with contemporary society, citizens need to be aware of the epistemic values, methods, and institutional practices of science. Given that the NOS is widely regarded as important, it is surprising, therefore, how little attention NOS has received in the context of research on science education for citizens, in comparison with the focus of research conducted in schools (Archer-Bradshaw 2017; Demirdöğen et al. 2016; Mansour et al. 2016). Within the framework of PUS, however, some attempts have been made to determine the views of citizens on certain aspects of the NOS. For instance, the international study of scientific culture commissioned by the BBVA Foundation (2012a, 2012b) considered public attitudes toward two key aspects of the NOS: the way in which knowledge is obtained and validated and the relative validity of a scientific theory. The same study also examined the public’s views regarding different dimensions of science, including the role of science in driving progress (improving health, challenging superstitions, etc.), science and ethics, science as a way of repairing environmental damage, the credibility of scientific institutions, and the public image of scientists. For its part, the European Commission (2010) published a survey of attitudes toward science and technology that touched upon certain aspects of the NOS, including the image of science and technology, the responsibilities of scientists and policymakers, and the effectiveness of European scientific research.

Recently, within the framework of PES, some institutions have put forward proposals regarding science education for citizens in which the latter are invited to participate in scientific debate. For example, the European Commission, in its report entitled Science Education for Responsible Citizenship (2015), proposed six key objectives and a set of recommendations that included citizen awareness of the NOS. The authors of the report argue that curiosity about the world around us, learning to act and think like a scientist and an innovator and understanding the nature of science – all provide a solid foundation for future success (European Commission 2015, p. 19). Similarly, a number of citizen science projects have investigated how public participation may influence scientific literacy. For example, the Citizen Sky Project examined (1) how volunteers' attitudes towards science and epistemological beliefs about the nature of science changed after six months of participation in an astronomy-themed citizen science project, and (2) how the level of project participation related to these changes (Price and Lee 2013, p. 773). In a similar vein, Bonney et al. (2016) argued that citizen science may enhance the public's understanding of science, including as regards procedures and the NOS. Other research on the NOS, such as the study by Laherto et al. (2018), examines the role that scientists themselves may play in informal learning contexts and science communication. These studies and reports, together with the findings of research on the NOS in science education, provide a platform from which to develop this field of knowledge. In order to do so, however, it is first necessary to clarify the key aspects of the NOS that citizens need to take on board.

An Approach of NOS for the Citizenship

Given the lack of an agreed theoretical framework for addressing the NOS in education we had, in this study, either to choose one particular approach or incorporate elements of different approaches. In making this decision, we not only considered our own views of the NOS but also took into account that (1) the focus of this study is science education for citizens and (2) the experts in the previous Delphi study came from different science- and technology-related fields, and hence their contributions reflected different aspects of science (epistemic, cognitive, social). Consequently, we opted to draw upon broader approaches to the NOS, especially those proposed by Hodson and Wong (2014), Irzik and Nola (2011), Osborne et al. (2003), and Erduran and Dagher (2014), without ignoring the contributions of other authors. We decided, however, not to include the aforementioned consensus view due to the limitations of this approach, as summarized by Kampourakis (2016), p. 674), and also because our aim, as stated above, was to identify aspects of the NOS that are key to citizen literacy in science, not those which should form the basis of formal science education in schools (Abd-El-Khalick 2012; Kampourakis 2016). This kind of scientific literacy is important because citizens need to be capable of acting not merely as users of science but as informed participants in science policy decisions, or even in scientific projects (Price and Lee 2013; Haywood and Besley 2014). The dimensions of the NOS we considered were as follows: (a) ideas about scientific knowledge, (b) ideas about the practice of science, and (c) ideas about the relationship of science to technology, society, and the environment. These dimensions, together with the goals and values of science, provide the overall framework that guides the present study.

Cognitive–epistemic considerations about the products of science (facts, laws, theories, models, etc.), how they are generated and what they consist of, correspond to the first of these dimensions, scientific knowledge. The second dimension, ideas about the practice of science, encompasses not only research activities (defining problems, conducting observations, collecting data, establishing hypotheses, developing models and theories) but also the methods, strategies, and techniques that give credibility to the work of scientists. It is under this dimension that we also consider the goals and values of science (objectivity, feasibility, critical analysis, etc.). Finally, the social dimension includes the professional activities of scientists (e.g., attending congresses, writing articles, and presenting conference papers), the social certification of their work, the social values of science (such as respect for the environment or utility in the fields of health and the economy, etc.), and other aspects of the relationship between science, society, and the environment.

Taking into account this approach of NOS for the citizenship, the present study aims to contribute to this goal by (1) examining the NOS themes identified by a panel of Spanish experts from different science-related fields and (2) determining the degree to which they agreed on these NOS themes.

Context of The Present Research

The starting point for the present study is a set of key aspects of scientific competence for citizens that were identified in a previous Delphi study (Blanco-López et al. 2015) in which we sought the views of 31 Spanish experts representing the following professional groups: seven scientists and engineers (SE), six researchers and/or private sector scientists (RP), six philosophers of science (PS), six science educators (ST), and six science communicators (SC) (two science journalists and four directors of Spanish science museums/centers). In creating these groups, we defined experts as those with acknowledged expertise in communicating, using, or researching the processes and practices of science (Osborne et al. 2003, p. 698). Participants were selected in collaboration with six advisers to the research project, who in addition to taking part in the pilot stage helped us to draw up a list of 53 experts, all of whom were distinguished representatives of the aforementioned professional groups in Spain. After being informed about the project, 31 of them accepted the invitation to participate.

The three rounds of the Delphi study had the following aims: gathering the experts' opinions about what science- and technology-related knowledge, skills, attitudes, or values citizens need to possess in order to participate effectively in the different areas of their lives (round 1); obtaining the experts' ratings of the relative importance of the aspects identified (round 2); and evaluation of the results (round 3).

Round 1 yielded a total of 40 aspects that we organized into six dimensions, three referring to knowledge (i.e., knowledge and understanding of the nature of science and/or technology, or of STS relationships; knowledge about general and/or specific aspects of science and technology; and knowledge and skills related to disciplines other than science) and three to other skills and attitudes (i.e., general skills and abilities; skills and abilities related to science; attitudes or values). For each aspect, we produced a summary that captured the core features of the experts' responses.

The Delphi analysis revealed five aspects about which there was a stable consensus of opinion across the study. In descending order based on the degree of consensus achieved in round 3, these aspects were (1) critical attitude/thinking; (2) individual responsibility; (3) ability to search for, analyze, synthesize, and communicate information; (4) ability to reason, analyze, interpret, and construct an argument in relation to scientific phenomena and knowledge; and (5) ability to work as part of a team (Blanco-López et al. 2015).

Methods

The present study involves a new analysis of the data and results obtained in the aforementioned Delphi study (Blanco-López et al. 2015), and it consisted of three stages: (1) identifying NOS elements and themes among the 40 aspects originally proposed by the panel of experts; (2) analysis of changes in the importance ratings awarded to these themes over the course of the Delphi study; and (3) analysis of variability across professional groups.

The first stage of the study consisted in identifying NOS elements (i.e., specific statements related to the NOS) among the 40 aspects initially identified in the Delphi study and determining which of them could be considered as NOS themes (Table 1), taking into account the recent literature (Duschl and Grandy 2013; NGSS Lead States 2013; Erduran and Dagher 2014; Hodson and Wong 2014) on this question in the context of science education (Kampourakis 2016). The process of identification therefore involved examining the descriptions, examples of contexts and, especially, the justifications offered by the experts for the aspects proposed in the first round of the Delphi study, together with their comments in the subsequent two stages, since most of the NOS elements are featured here. It should be noted that the experts were provided with summaries of the aspects in rounds 2 and 3 of the Delphi process, and thus, they had the opportunity to comment critically on them; their own views could also, in theory, be influenced by the content of the summary document.

In line with the dimensions of our approach and those of other authors with a broad focus, especially with the approach of Hodson and Wong (2014), we considered that an aspect could be classified as NOS if it reflected one or more of the following criteria: (a) characteristics of scientific knowledge as generated through the application of scientific methods; (b) characteristics of scientific practice, both methodological and professional, and including epistemological assumptions, values, and interests; or (c) relationship of science to technology, society, and the environment.

The second stage involved an analysis of change in the ratings awarded to each of the themes thus identified as NOS, taking into account the professional group(s) that proposed each aspect and the degree of consensus and stability achieved as regards its importance. Here, we began by counting the number of themes proposed by each professional group in round 1, and then, in order to analyze the degree of consensus and stability of opinion, we compared the ratings awarded to each theme in rounds 2 and 3. The degree of consensus and stability was established by applying the criteria proposed by Osborne et al. (2003). Thus, consensus was defined as a minimum of two thirds (66%) of the experts rating a theme as $\geq$ 4 (on a 5-point Likert scale), while stability was defined as a shift of one third or less in their ratings between rounds 2 and 3.

In the third and final stage, we analyzed differences between the different professional groups in their importance ratings of the NOS themes. Analysis of variance with post hoc Scheffé test was used to identify any significant differences between the groups in their round 3 ratings.

Results and Discussion

In what follows we present the results of this new analysis according to the three stages described above.

Identifying NOS Elements and Themes in the Delphi Study

Application of the aforementioned three criteria to the 40 aspects originally identified in the Delphi study (Blanco-López et al. 2015) indicated that 12 of them could be considered as NOS themes (Table 1) comprising one or more NOS elements, and that NOS elements were also present in a further four aspects (Table 2). It should be noted at this point that the way in which the aspects in the original Delphi study were formulated reflects the question that the experts had to consider in round 1, that is, they were asked to list key aspects of scientific competence (knowledge, skills, attitudes, and values) for citizens.

Table 1 NOS elements and themes and the aspects identified in the previous Delphi study to which they correspond

NOS elements	NOS themes (aspects in the Delphi study)
Science is not a dogma. Science cannot explain everything.	Theme no. 1. Science versus other human activities for generating knowledge (Aspect no. 26. Understanding of what science is and how it differs from other human activities)
Science changes over time. Science proceeds through critique and reasoning. Science is essential for understanding the world. Science is essential for improving the world. The scientific way of understanding the world, based on reasoning, is more valid than is religion or other nonrational forms of understanding characteristic of bygone eras. Science competes in different contexts with other less rational ways of interpreting the world.	Theme no. 2. Rationality (Aspect no. 18. Appreciation of scientific results and an approach based on scientific reasoning)
Science requires the precise use of language, logical argument, and mathematics.	Theme no. 3. The language of science (Aspect no. 33. Understanding of and the ability to use scientific language)
Scientific knowledge is conjectural. Scientific knowledge is fallible. Scientific knowledge is provisional. Scientific knowledge is partial.	Theme no. 4. Nature of scientific knowledge (Aspect no. 24. Basic understanding of the nature of scientific knowledge)
The scientific method is the instrument of science. There is not a single scientific method, but rather scientific methods.	Theme no. 5. The methods of science (Aspect no. 23. Knowledge about and an understanding of the scientific method)

Defining and solving problems is what enables progress in science and technology.	Theme no. 6. The role of problem definition and problem solving in science (Aspect no. 6. Ability to solve problems)
Observation is important for scientists and technologists.	Theme no. 7. Observation (Aspect no. 5. Ability to observe)
Observation is the most important driver of knowledge in the experimental sciences.	
Hypotheses play an important role in focusing research activity.	
Critical attitude is essential for scientists.	Theme no. 8. Critical attitude
A critical attitude is important in various spheres; it is not specific to science.	(Aspect no. 1. Critical attitude/thinking)
Curiosity is essential for generating scientific knowledge.	Theme no. 9. Curiosity (Aspect no. 9. Curiosity and interest)
The work of scientists is tentative.	Theme no. 10. Scientific work
The work of scientists is creative.	(Aspect no. 30. Understanding of scientific work)
The work of scientists is social.	
Scientists should do more to raise public awareness about science-related problems.	
Science makes a positive contribution to society and the environment, but it can also have a negative impact.	Theme no. 11. Relationship between science–technology–society and the environment (Aspect no. 28. Knowledge about the relationship between science–technology–society and the environment)
Citizens in the risk society are not reassured by technologists.	Theme no. 12. The role and function of technology and of people's relationship to it
Technology helps citizens to see the direction that society is taking.	(Aspect no. 27. Understanding of the role and function of technology, and of people's relationship to it)

Table 2 Other NOS elements and the aspects identified in the previous Delphi study to which they correspond

Other NOS elements	Aspects in the Delphi study
Science has its limits.	Aspect no. 28. Knowledge about the relationship between science–technology–society and the environment Aspect no. 23. Knowledge about and an understanding of the scientific method
Science encourages rationality.	Aspect no. 23. Knowledge about and an understanding of the scientific method
Technology is not merely the application of science.	Aspect no. 27. Understanding of the role and function of technology and of people's relationship to it
Mathematics, physics, and chemistry are the bedrock of most scientific and technological activities.	Aspect no. 16. Basic mathematical knowledge
Scientific knowledge has an empirical basis.	Aspect no. 3. Ability to analyze
Science can be the cause of ecological problems and also offer solutions.	Aspect no. 18. Appreciation of scientific results and an approach based on scientific reasoning
Knowledge of science leads to greater awareness of social and environmental problems related to science.	Aspect no. 22. Knowledge about the environment
Scientific knowledge can lead to the betterment of the individual and society.	Aspect no. 21. Knowledge about the origin of life and evolution

In the present study, we have modified slightly the wording of the 12 aspects that were identified as being related to the NOS so as to better reflect this quality, and we also refer to them as themes rather than aspects so as to distinguish the present from the previous analysis (see Table 1).

It can be seen in Table 3 that some of the 12 themes met more than one of the criteria, thereby reinforcing their consideration as NOS. The majority of the NOS themes fulfilled criterion (b) (Characteristics of scientific practice), while a smaller number of them reflected criterion (a) (Characteristics of scientific knowledge) and criterion (c) (STSE). These results are consistent with the broader view of what constitutes the NOS (Duschl and Grandy 2013; Erduran and Dagher 2014; Hodson and Wong 2014; NGSS Lead States 2013).

Table 3 Themes identified in the Delphi study that met one or more of the three criteria for consideration as NOS themes

Theme	Criteria		
	a	b	c
1. Science versus other human activities for generating knowledge	X	X	X
2. Rationality	X	X	X
3. The languages of science		X	
4. Nature of scientific knowledge	X	X	X
5. The methods of science		X	
6. The role of problem definition and problem solving in science		X	
7. Observation		X	
8. Critical attitude	X	X	
9. Curiosity	X	X	
10. Scientific work		X	X
11. Relationship between science–technology–society and the environment	X		X
12. The role and function of technology and of people’s relationship to it			X

Criteria: (a) characteristics of scientific knowledge as generated through the application of scientific methods; (b) characteristics of scientific practice, both methodological and professional, and including epistemological assumptions, values, and interests; (c) influence of science on society and the environment

In addition to the 12 themes listed in Table 1, some of the experts also proposed Knowledge about how the main ideas on which science and technology are based have developed, which would correspond to what in the classification of Norris (2014) is labeled as about the nature of science. The relevance of this aspect, which did not meet our criteria for NOS, was primarily attributed to the importance in science of freedom of thought.

Description of the NOS Themes Identified

In this section, we describe in greater detail each of the 12 NOS themes and their corresponding elements (Table 1) and draw upon comments made by the panel of experts to illustrate how the themes were understood and, where relevant, any discrepancies that emerged.

Science Versus Other Human Activities for Generating Knowledge

This theme refers to the statements made by experts regarding what scientific knowledge entails in general and how it is generated in comparison with other approaches to understanding the world in which we live. For example, one of the science communicators stated: An understanding of the value of science, of what it is and isn't, of the vision that science offers for studying the world in which we live. It is not a dogma, nor an answer to everything. It changes over time, and its method is based on critique and reason (SC4). This comment illustrates four of the NOS elements that comprised this theme: Science is not a dogma, Science cannot explain everything, Science changes over time, and Science proceeds through critique and reasoning (Table 1). The other two elements were Science is essential for understanding the world and Science is essential for improving the world, reflecting the enormous importance that is ascribed to science: It [science] is essential if we want to understand the world we live in, or if we want to make the world a better place. (SC4)

It was also argued that citizens need to understand the nature of science because of the mistaken and partisan ideas to which they are routinely exposed and which make it difficult for them to know what counts as genuine scientific knowledge: The average citizen must be capable of distinguishing between science and that which purports to be science but which in fact generates a lot of hot air rather than reliable and tested knowledge. (SC3)

It is worth highlighting that the experts' statements closely reflected the characteristics of science as described in the literature on NOS.

Rationality

In relation to this theme, the experts expressed concern over the rise in recent years of antiscience movements, which they argued were slowly undermining the scientific attitude. One of the philosophers of science put it as follows: Certain social, political, and religious movements that arose during the second half of the twentieth century are disseminating — including in countries with highly developed education systems — attitudes that are not merely critical of science but openly hostile towards it. This is occurring both from positions regarded as progressive (radical ecology, new age, the rise of 'alternative sciences', etc.) and those considered to be reactionary (creationism, intelligent design, etc.). Citizens need to be equipped to counter these anti-science movements (PS3). This concern is reflected in the elements The scientific way of understanding the world, based on reasoning, is more valid than is religion or other non-rational forms of understanding characteristic of bygone eras and Science competes in different contexts with other less rational ways of interpreting the world, as exemplified by the following statement (PS3): Is there any scientific basis for the criticisms that religious movements are nowadays making of evolutionary theory? Is it right that a supposedly serious radio program phones up some amateur forecaster to tell us what the weather will be like two weeks hence during the Easter holidays?

The Languages of Science

The experts placed considerable emphasis on the language of science, both that used for communication between scientists and formal systems such as mathematics. This is reflected in the element Science requires the precise use of language, logical argument, and mathematics and is illustrated through the following statements:

> Science requires a precise use of language, and cognitive knowledge relies on this marvelous tool. Reasoning in science occurs through a particular set of words, syntax, grammar, etc. (SE3)
>
> Science shows that opinions can be well founded, that arguments can be logical. It is a language in which there is room for debate and from which conclusions can be drawn that are useful to us all. (SC4)
>
> Mathematics is also a kind of language, an internally consistent code that allows events to be described in terms of models and equations whose elements are linked through coherent and logical laws. (SE3)
>
> One of the science communicators (SC4) considered that the widespread lack of familiarity with scientific language was the reason why some people were wary of certain technological developments: I would argue that one of the reasons why many people, and even some politicians, have adopted such a negative view of cellphone masts is because they don't understand scientific language or statistics, and so they operate on the basis of prejudice and fears. (SC4)

Nature of Scientific Knowledge

This theme was proposed by one of the philosophers of science (PS1), who believed that the public should have a basic understanding of the conjectural, fallible, provisional, and partial nature of scientific knowledge. This view is common within the literature on the NOS, and hence, we consider this theme to comprise the elements mentioned in this statement, namely that scientific knowledge is conjectural, fallible, provisional, and partial.

One of the science communicators (SC5) referred to climate change as an example of a complex topic about which many people are skeptical as they are unfamiliar with the nature of scientific knowledge, especially as regards the aforementioned elements: The public are confused by the contradictory information about climate change. A lack of awareness that scientific knowledge is provisional can lead (and in fact it already has) to indiscriminate skepticism, it's the confusion that arises from the impossibility of absolute certainty in relation to complex issues that are continuously open to debate (which is the case for the majority of the big scientific questions of our day). (SC5)

The Methods of Science

One of the science communicators (SC6) argued that the scientific method was the instrument through which science itself was created, while another (SC5) stated: The experimental method is the very core of scientific methodology, and it is only this knowledge that allows us to explain why natural phenomena occur and to understand the applications of technology. These ideas are reflected in the element we labeled The scientific method is the instrument of science.

In round 2 of the Delphi study, a number of criticisms were expressed regarding a rigid notion of what scientific activity actually entails. For instance: For some time now, scientists in different fields have avoided using the expression ‘scientific method’, as this might suggest there is a set of infallible recipes for how to go about things. Some authors have opted to speak of scientific methods, in the plural, or refer to scientific activity, etc. (ST2); or Rejecting the very idea of a single ‘scientific method’, a set of clearly defined rules that can be mechanically applied regardless of the research context. (ST3). These views are captured by the element: There is not a single scientific method, but rather scientific methods.

The Role of Problem Definition and Problem Solving in Science

Under this theme, the experts not only suggested that citizens need to acquire this ability but also highlighted the important role that problem definition and solving plays as a driver of scientific and technological progress. This is reflected in the NOS element we refer to as Defining and solving problems is what enables progress in science and technology, and is illustrated by the following statement:

> Science and technology progress because people pose problems and look for possible solutions, analyzing past experiences and potential strategies that have been used before in other contexts, comparing possibilities and drawing conclusions. (SE1)

Observation

Although, in the Delphi study, this aspect was formulated as an ability, the comments made by experts referred primarily to the role of observation in scientific research. A clear example of the element we label Observation is important for scientists and technologists is the following statement, made by an engineer: I think this is an essential aspect for scientific competence, although in my view it is more important for those people who are going to work within the field of science or technology. (SE5)

Overall, however, the experts disagreed about the importance that should be ascribed to this element. On the one hand, the element we refer to as Observation is the most important driver of knowledge in the experimental sciences derives from comments such as the following:

> It has been the most important driver of knowledge in the experimental sciences that aim to determine causality. (SE3)

> When conducting research you need to be meticulous in observing all the details, even things that may appear to be of no relevance, because later, through repeated experiments, you discover that they were not a chance occurrence. (RP2)

Other experts, however, were critical of these opinions and suggested that they risked equating science with an empiricist–inductivist view:

> In my opinion it's not correct to say that observation '...has been the most important driver of knowledge in the experimental sciences'. This might suggest that scientific activity is only what corresponds to the empiricist view... So I think it would be better to refer to the ability to pose problems, to establish hypotheses… or if we are to retain the term 'observation', then it needs to be defined more clearly so as to avoid any erroneous interpretations. (ST2)

> Why emphasize this ability rather than, say, the ability to establish plausible hypotheses that can be tested? This is reinforcing an empiricist-inductivist view that does not reflect what scientists actually do. This empiricist idea that observation is the basis of scientific work overlooks the key role that hypotheses play in helping us to focus our research on a particular problem. (ST3)

The importance ascribed here to hypotheses is reflected in the element Hypotheses play an important role in focusing research activity.

Critical Attitude

The experts attributed enormous importance to Critical attitude (e.g., In addition, I would emphasize again that a critical attitude is essential for scientists, by which I mean anybody who works in science (SE5)), hence the element we refer to as Critical attitude is essential for scientists. Related to this theme, the experts also felt that citizens should be able to engage in critical thinking of the kind they associated with science: The informed acquisition of an anti-dogmatic scientific attitude, the ability to critique (ST6).

However, there was some disagreement during rounds 2 and 3 regarding the extent to which citizens needed to acquire such an attitude and its utility in different contexts. As one of the engineers stated: I think this is an essential aspect for scientific competence, although in my view it is more important for those people who are going to work within the field of science or technology rather than for citizens in general (SE5). The same expert went on to say: But I do think that a critical attitude is important in other spheres of people's lives, in other words, it's not a specifically scientific competence, but rather is applicable to other areas of knowledge (for example, a citizen's knowledge of history, economics or even politics). To put it another way, it's a competence that cuts across different spheres (SE5). These opinions are reflected in the element labeled A critical attitude is important in various spheres, it is not specific to science.

It should also be noted that the idea of Critical attitude was explicitly mentioned in relation to some of the other NOS themes identified. It was also implicitly alluded to when the experts highlighted how an understanding of the nature of scientific knowledge and the way that researchers worked could both prevent citizens from being taken in by dogmatic ideological positions and help them to make informed decisions.

Curiosity

The experts regarded curiosity as being essential in science. The element we label Curiosity is essential for generating scientific knowledge is reflected in the following statements:

> Scientific knowledge cannot be generated without curiosity, the desire to understand and explain, although of course, some people are happy to settle for a magical world. (SE3)
>
> Without curiosity there's no observation, no questions, no answers…. (SE3)

Scientific Work

The experts also suggested that citizens need to understand the nature of scientific work, that is, the characteristics of scientific practice, both methodological and professional, and including epistemological assumptions, values, and interests. In our view, scientific work includes but encompasses more than the methodological aspects of science (scientific methods), which are reflected in the aforementioned NOS theme The methods of science. Hence, the present theme includes a number of other elements, indicating that the work of scientists is tentative, creative, and social.

In terms of why the experts considered that citizens should understand the nature of scientific work, the argument used was similar to that used in relation to a previous theme (i.e., Science versus other human activities for generating knowledge): It's about challenging mistaken and impoverished views of what scientists do (ST3). Note that the experts' comments in relation to this theme once again reflect aspects mentioned in the NOS literature.

A concern for social and environmental issues is reflected in the element Scientists should do more to raise public awareness about science-related problems, as illustrated in the following statement: Public awareness about climate change has been raised more by environmental pressure groups or the campaign of a well-known politician than it has by the work of the scientists who are providing them with their data (SC4).

Relationship Between Science–Technology–Society and the Environment

The impact of science and technology on modern society, and vice versa, was also regarded by the experts as an important aspect that citizens should be aware of: Citizens need to be able to weigh up the place of science in their world, to consider its contributions, its negative repercussions, and also its limits. They also have to understand and contemplate its role in our civilization and in relation to the environment, considering ethical aspects, costs and benefits. (ST5). This view is reflected in the element Science makes a positive contribution to society and the environment, but it can also have a negative impact.

The Role and Function of Technology and of People's Relationship to It

One of the science communicators (SC4) in the Delphi study described this aspect as follows: Aspects related to the role and function of technology. Control over technology, its effects (including harmful ones), the impossibility of zero risk, the evaluation of costs and benefits.... The same expert went on to express a certain pessimism with regard to the contribution of technologists: It disturbs us to think that we are living in a risk society, and we are not reassured by what the technologists are showing us. (SC4). This opinion is reflected in the element Citizens in the risk society are not reassured by technologists. Another expert (RP1) offered a more positive view of the contribution that technology makes: It helps us to see more of where the intellectual climate of the day is taking us. (RP1), hence the element Technology helps citizens to see the direction that society is taking.

How Do the Identified NOS Themes Compare with Other Research?

In order to examine whether the NOS themes proposed by the experts in our previous Delphi study are in line with those discussed in the literature, we compared our findings with the content of seven publications that, overall, may be considered representative of current views on the NOS. Table 4 shows the results of this comparison.

Table 4 Comparison of the 12 NOS themes identified with the content of seven publications

Theme	Studies						
	Abd-El-Khalick (2012)	Bartos and Lederman (2014)	Eastwood et al. (2012)	Erduran and Dagher (2014)	Hodson and Wong (2014)	Osborne et al. (2003)	Aragón Méndez et al. (2018)
1. Science versus other human activities for generating knowledge		X					
2. Rationality							
3. The languages of science					X		
4. Nature of scientific knowledge							X
5. The methods of science	X			X		X	X
6. The role of problem definition and problem solving in science		X	X	X		X	
7. Observation		X		X		X	X
8. Critical attitude				X	X	X	
9. Curiosity							
10. Scientific work	X	X	X			X	
11. Relationship betweenscience–technology–society and the environment	X	X	X	X	X		X
12. The role and function oftechnology and of people's relationship to it							

It can be seen in Table 4 that the 12 NOS themes we identified show a heterogeneous distribution across the seven publications considered. Six of the 12 themes feature in at least four of these publications, and three do not appear in any of them. The comparison also shows that all the publications mention at least three of the themes identified here and that the broadest spread (five themes) is found in the studies by Bartos and Lederman (2014), Erduran and Dagher (2014), and Osborne et al. (2003).

The theme we labeled as Relationship between science–technology–society and the environment is the one that appears most often (in six of the seven publications), while The methods of science, The role of problem definition and problem solving in science, Observation, and Scientific work are present in four, and Critical attitude features in three. This illustrates how the themes which attract the greatest attention in the seven selected publications have to do with scientific activity, STSE relationships, and values.

At the other extreme, three of the NOS themes we identified (i.e., Rationality, Curiosity, and The role and function of technology and of people's relationship to it) do not feature in any of the publications considered. A further three (i.e., Science versus other human activities for generating knowledge, The languages of science, and Nature of scientific knowledge) appear in one of the other publications. As to why some of our NOS themes are absent from, or poorly represented in, the other publications, may be due to the fact that they are formulated in very general terms.

Change in the Importance Ratings of NOS Themes

In the second stage of the present study, we analyzed which professional group proposed each of the NOS themes and the corresponding degree of consensus and stability that was achieved for each across the Delphi study.

Which Professional Group(s) Proposed the NOS Themes?

The different professional groups varied considerably in the number of NOS themes they proposed in round 1 of the Delphi study (Table 5).

Table 5 Professional group(s) that proposed each of the 12 NOS themes in round 1 of the Delphi study

Theme	Professional group				
	SE (n = 7)	RP (n = 6)	ST (n = 6)	PS (n = 6)	SC (n = 6)
1. Science versus other human activities for generating knowledge				PS3 PS4	SC3 SC4
2. Rationality				PS3	
3. The languages of science	SE3				SC4
4. Nature of scientific knowledge				PS1	SC5
5. The methods of science				PS1	SC2 SC5 SC6
6. The role of problem definition and problem solving in science	SE1 SE4				
7. Observation	SE3	RP2 RP6			
8. Critical attitude	SE4	RP1	ST1 ST4 ST6		
9. Curiosity	SE3 SE7	RP6			
10. Scientific work			ST3		SC4
11. Relationship between science–technology–society and the environment			ST1 ST2 ST3 ST5		
12. The role and function of technology and of people's relationship to it		RP1			SC4
Number of proposals by each professional group	7	5	8	5	9
Number of experts in each group who proposed a theme	4	3	6	3	5

If we consider the number of proposals by each professional group, the combined total for the ST and SC groups is the same as that for the other three groups, and almost the same if we consider the number of experts in each group who proposed a theme. These differences are likely due to the kind of professional activity engaged in by the various experts (i.e., those who work as scientists [SE and RP] vs. those who work with science [ST, PS, and SC]), and the results are consistent with the fact that reflecting upon science is a core feature of the work of science educators, communicators, and philosophers of science. However, the results for the PS group do not fit with this explanation as, along with the researchers and/or private sector scientists (RP), they proposed the lowest number of NOS themes.

There was also considerable variability in the number of experts who proposed the different NOS themes. While the majority of the themes (8 of 12) were proposed by two professional groups, three of them were mentioned by just one group: The role of problem definition and problem solving in science was proposed by two scientists/ engineers (SE), Rationality by one of the PS, and the Relationship between science– technology–society and the environment by four ST. The latter result likely reflects the relevance of STSE relationships within the context of science education, the specific field of the ST group. Finally, it is important to note that the remaining theme, Critical attitude, was proposed by a majority of the professional groups (specifically, it was referred to by three groups and five different experts).

Table 6 Consensus regarding the 12 themes considered in round 3 of the Delphi study and stability of opinion between rounds 2 and 3

Theme	Consensus round 3	Stability rounds 2–3
1. Science versus other human activities for generating knowledge	✗	✗
2. Rationality	✗	✓
3. The languages of science	✗	✗
4. Nature of scientific knowledge	✗	✗
5. The methods of science	✗	✓
6. The role of problem definition and problem solving in science	✓	✗
7. Observation	✓	✗
8. Critical attitude	✓	✓
9. Curiosity	✓	✗
10. Scientific work	✗	✓
11. Relationship between science–technology–society and the environment	✗	✗
12. The role and function of technology and of people's relationship to it	✗	✓

Degree of Consensus and Stability

As part of our previous Delphi study, we also examined the degree of consensus in round 3 and the stability of opinion between rounds 2 and 3 as indicators of which themes should be considered the most important. The criteria used for this task are described above in the Methods section. The results for consensus and stability of the 12 NOS themes are shown in Table 6.

As can be seen in Table 6, a stable consensus was only observed for one of the 12 NOS themes: Critical attitude. The themes we labeled as The role of problem definition and problem solving in science, Observation, and Curiosity achieved consensus but not stability, and no consensus was observed for any of the remaining NOS themes. It should be noted that of the 40 aspects originally proposed by our panel of experts, Critical attitude was awarded the highest importance rating (mean of 4.52 out of 5 in round 3).

The importance that our experts ascribed to this theme in the context of science education for citizens is consistent with the view of other authors who have considered the NOS in detail (Erduran and Dagher 2014; Hodson and Wong 2014; Irzik and Nola 2011). For instance, one of the components that Hodson and Wong consider to be key for achieving cultural and civic scientific literacy is a commitment to critical understanding of contemporary socio-scientific issues at the local, regional, national and global levels, including their historical roots and underlying values, together with a willingness to take appropriate and responsible action, and [to] encourage others to do so (Hodson and Wong 2014, p. 2643). Similarly, Erduran and Dagher (2014) identify critical examination as one of the aims or values of science education, and they refer to critical thinking as a professional skill required by all scientists. For their part, Irzik and Nola (2011) consider a critical attitude to be an important aspect of the NOS and argue that science is a special kind of critical investigation.

Of the 11 NOS themes for which we observed no stable consensus, five (i.e., Scientific work, The methods of science, The role of problem definition and problem solving in science, Observation, and Relationship between science–technology–society and the environment) are discussed in several of the other publications we considered for comparison purposes. By contrast, we found few references to the other six: Science versus other human activities for generating knowledge, Nature of scientific knowledge, Rationality, The languages of science, Curiosity, and The role and function of technology and of people's relationship to it.

Variability Across Groups

Table 7 shows the results obtained when analyzing differences in the importance ratings awarded to the 12 NOS themes by the five professional groups.

It can be seen in Table 7 that a significant difference between professional groups was observed for six of the 12 NOS themes, most commonly between ST and RP, whose importance ratings differed significantly in relation to three themes: The role and function of technology and of people's relationship to it, Scientific work, and The languages of science. The ratings of science educators (ST) also differed significantly from those of the SE group on one theme: The languages of science.

The PS and RP groups differed significantly in their ratings of two themes: Nature of scientific knowledge and Science versus other human activities for generating knowledge. The PS also differed from the SE group in relation to one theme: Nature of scientific knowledge.

A significant difference in the ratings of more than two professional groups was only observed for two themes: Nature of scientific knowledge (PS vs. SE and PS vs. RP) and The languages of science (ST vs. SE and ST vs. RP).

A possible explanation for these results may be found in a point we made earlier when discussing which professional groups proposed the various NOS themes. Thus, those professionals whose work primarily involves doing science (i.e., SE and RP) award significantly lower importance ratings to NOS themes than do those whose

Table 7 Results of an ANOVA showing the NOS themes for which there were significant differences between professional groups in round 3 of the Delphi study (adapted from Blanco-López et al. 2015)

Theme	ANOVA test		Post hoc (Scheffé)*
	F	P	
1. Science versus other human activities for generating knowledge	3.92	.02	PS vs. RP
2. Rationality	2.03	.13	
3. The languages of science	4.54	.01	ST vs. SE ST vs. RP
4. Nature of scientific knowledge	7.33	.00	PS vs. SE PS vs. RP
5. The methods of science	1.29	.30	
6. The role of problem definition and problem solving in science	4.33	.01	ST vs. PS
7. Observation	2.23	.10	
8. Critical attitude	.72	.59	
9. Curiosity	1.47	.24	
10. Scientific work	5.11	.01	ST vs. RP
11. Relationship between science–technology–society and the environment	2.88	.05	
12. The role and function of technology and of people's relationship to it	3.93	.02	ST vs. RP

*The highest ratings correspond to the group that is listed first

professional activity is centered around reflection on science (ST and PS). The exception here is the SC, whose ratings did not differ significantly from those of the SE and RP groups.

Other NOS Elements

In addition to the elements included in the NOS themes described above, we identified a further eight elements in statements corresponding to eight aspects in the Delphi study (Table 2). Four of these eight elements correspond to aspects that we do not consider to be NOS themes, while the remaining four were not included in the corresponding themes as they differed considerably from the defining elements.

Science has its limits, Science encourages rationality, Technology is not merely the application of science and Mathematics, physics, and chemistry are the bedrock of most scientific and technological activities are elements that express general ideas about science and technology. The element Science has its limits appears in two aspects and is illustrated by the following statements:

> Citizens need a balanced appreciation of science, what it can contribute, its negative repercussions, and also its limits. (ST5)

> And hence this knowledge also means an awareness of its limits, of the phenomena that can't be addressed through experiments and which require a different kind of approach. (SC5)

The other three elements are reflected, respectively, in the following three statements:

It offers people a convincing alternative to magic and other beliefs that merely serve to subjugate those who are already socially disadvantaged. (SC6)

It's about much more than the practical application of more abstract science […]. (SC4)

Mathematics, along with physics and chemistry, is the bedrock of most scientific and technological activities. (RP1)

The experts also expressed ideas about scientific knowledge, which we reflect in the element Scientific knowledge has an empirical basis. This is a characteristic of scientific knowledge that is widely referenced in the literature on the NOS, and it is illustrated by the following statement:

It is essential in all scientific work to start from an understanding of reality, and even the most creative forms of scientific activity must be based on this. (RP3)

The statements made by experts also included ideas concerning the relationship of science to society and the environment, leading us to define three elements: Science can be the cause of ecological problems and also offer solutions, Knowledge of science leads to greater awareness of social and environmental problems related to science, and Scientific knowledge can lead to the betterment of the individual and society. These elements are reflected in the following comments:

Is science to some extent responsible for the ecological crisis? Can science offer solutions to ecological problems? (PS3)

It's one of the most important failures in recent generations and it's led to a widespread lack of environmental awareness. It could all change if new generations had an environmental awareness derived from basic knowledge of the natural sciences. (RP1)

The idea of a world that is governed by the laws of natural selection, well, at first it might seem disappointing, such a simple process, but it can become reassuring, this vision of a more orderly world, more patient, in which the species is much more important than the individual. And that can encourage tolerance, respect for others, taking a lot of the stress off in the process. (SC6)

Conclusions and Implications

Debate continues as to the relationship that should exist between science and the general public (Haywood and Besley 2014; Irwin 2006; Pieczka and Escobar 2013; Rowe and Frewer 2005) and the kind of science education that citizens should ideally receive. The aim of the present study was to identify NOS aspects among the key scientific competences for citizenship identified by a panel of Spanish experts.

The results of our analysis lead us to draw the following conclusions:

& NOS aspects are an important component of science education for citizens. Of the five aspects for which we observed a stable consensus of opinion in our previous Delphi study (Blanco-López et al. 2015), one referred to the NOS. Furthermore, 12 of the 40 aspects that were originally proposed by the experts could be regarded as NOS themes, and a further four contained NOS elements, that is, specific statements concerning the nature of science. Overall, 37 NOS elements were identified in the present study, a finding which acquires added importance if one considers the question that the experts were asked to consider: What aspects (knowledge, skills, attitudes, or values) of science and technology should form part of citizens' awareness so that they are able to participate effectively in the different areas of their lives? Clearly, the scope of this question goes well beyond the NOS. & The NOS theme over which there was a stable consensus of opinion in our study, namely Critical attitude, does not feature in reports that adopt a consensus view (Abd-El-Khalick 2012; Bartos and Lederman 2014; Eastwood et al. 2012). By contrast, it is ascribed considerable importance in the work of Erduran and Dagher (2014), Hodson and Wong (2014), Irzik and Nola (2011), and Osborne et al. (2003), who take a broader view of what the NOS entails. This theme, along with many others, especially those associated with the consensus view, is considered by various authors (see, for example, the analysis by Kampourakis 2016) and some of the experts surveyed in our Delphi study to be an aspect common to a range of human activities, not merely science. We nonetheless consider it to be a key aspect of scientific activity and that science provides a privileged context for its development (Osborne 2014; Blanco-López et al. 2017; Wiblom et al. 2017).

- The results support the well-documented difficulty in defining and selecting the NOS aspects which citizens should ideally acquire. Only one of the 12 NOS themes we identified was unanimously agreed by our experts to be important. The importance ratings ascribed to the other 11 varied considerably.
- In general, those experts whose professional activity primarily involves reflection about science (i.e., ST and SC) proposed more aspects than did their peers whose work centers around the practice of science (i.e., SE and RP). The exception was the PS, whose work is of a reflective nature but whose responses were similar to those of the applied scientists (SE and RP).
- Overall, the NOS themes identified in this study constitute a broad set of themes that appear to varying degrees in the key reports on science education and the NOS (from both the consensus view and approaches critical of it) that we considered for comparison purposes (Abd-El-Khalick 2012; Bartos and Lederman 2014; Eastwood et al. 2012; Erduran and Dagher 2014; Hodson and Wong 2014; Osborne et al. 2003). In terms of the criteria established for this study, the NOS themes and elements identified are closely linked to the practice of science.

The present study is limited by certain features of the Delphi study on which it is based (Blanco-López et al. 2015) and also, potentially, by the decisions that had to be made as a consequence. One major limitation is the fact that the panel of experts in the Delphi study were asked to propose important aspects of science in general, not exclusively those related to the NOS. Caution was therefore required in the present analysis, since it was difficult to determine the extent to which the experts were intentionally highlighting the NOS content of certain aspects, as well as the importance they ascribed to this content.

A further and related limitation is that our starting point here was the list of 40 aspects of science, as categorized in round 1 of the previous Delphi study. Hence, in order to identify those that could be considered as being related to the NOS, it was necessary to return to the comments and justifications made by the experts in that study. As for the present analysis, the findings are potentially limited by the criteria we used to define a NOS theme, since these were derived from a select series of reports (Duschl and Grandy 2013; Erduran and Dagher 2014; Hodson and Wong 2014; NGSS Lead States 2013) that may not necessarily cover all approaches to this question. We are aware that this is a controversial field and, therefore, that a different set of criteria for defining the NOS may have produced different results.

While acknowledging these limitations, we believe that our study makes a useful contribution to the field by providing empirical support for the importance of one NOS theme (i.e., Critical attitude) in relation to science education for citizens. An understanding of how scientists work and build knowledge, and of the relationships between science, society, and the environment, can help the public to form a more nuanced and critical view of the discipline, thereby fostering a more democratic relationship between science and citizens of the kind discussed in the literature on PES (Bauer 2014; Michel 2012; Ryan 2015; Sturgis 2014) and citizen science (Price and Lee 2013). Acquisition of the abilities encapsulated by the aforementioned theme can play a key role in achieving this goal.

Although an awareness of the NOS can benefit citizens throughout their lives, it is an issue that is rarely addressed in schools, and even less so in contexts of informal and nonformal lifelong learning (Perrenoud 2012; Price and Lee 2013; Stiglitz and Greenwald 2016). In our country, for instance, NOS content now features strongly in the new education curricula (see Vázquez-Alonso and Manassero-Mas 2017; Vázquez-Alonso et al. 2013) for all science and technology subjects. However, this content is not accompanied by an explicit curriculum-wide proposal regarding how the NOS should be taught, and as a result, there is no clearly differentiated and structured approach to doing so (Vázquez-Alonso and Manassero-Mas 2017). In this respect, much work remains to be done. For our part, we are now considering a further study in which the NOS elements identified here form the starting point for a more detailed examination of what citizens need to know about the nature of science.

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Compliance with Ethical Standards

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

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