Cite this article:

García-Carmona, A. (2021). Improving pre-service elementary teachers' understanding of the nature of science through an analysis of the historical case of Rosalind Franklin and the structure of DNA. *Research in Science Education*, *51*(2), 347-373. https://doi.org/10.1007/s11165-018-9798-4

Improving Pre-service Elementary Teachers' Understanding of the Nature of Science through an Analysis of the Historical Case of Rosalind Franklin and the Structure of DNA

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Abstract. This qualitative study analyses how effective an activity based on the critical and reflexive reading of the historical case of Rosalind Franklin and the elucidation of the molecular structure of DNA can be for learning about the nature of science (NOS). The aspects of NOS addressed are the plurality of methods in scientific research, research objectives, the strengths of scientific models, and the epistemic and non-epistemic obstacles faced by scientists in the course of their research. The activity was implemented during a Science Teaching course for pre-service elementary teachers (PETs). The data were extracted from the PETs' reports, analysing them with a rubric based on inter-rater agreement. The results showed the PETs to have overall improved their understanding of the different NOS aspects addressed, and that they gave more importance to non-epistemic than to epistemic factors. In short, the results showed this type of activity to be educationally effective in learning about NOS using cases from the history of science. They also lent support to the view that teaching NOS should take an equilibrated approach to both its epistemic and non-epistemic aspects.

Keywords: DNA; history of science; nature of science; pre-service elementary teacher; Rosalind Franklin; science education.

INTRODUCTION

Nowadays a basic understanding of the nature of science (NOS) is considered to be a key pillar of citizens' scientific literacy (Clough, 2018; Hodson, 2014; NGSS, 2013; OECD, 2017). Somewhat more than two decades ago, Driver, Leach, Millar and Scott (1996) were already speaking of utilitarian, democratic, cultural, axiological, and educational reasons for integrating a basic knowledge of NOS into school science curricula. In the same vein, Shamos (1995) argued that when people evaluate public issues related to science and technology they usually resort to their (more or less well informed) knowledge of NOS. Also, Bybee (1997) established that an understanding of NOS forms part of the highest level of citizens' scientific literacy. Currently, there exist some framework programs of innovation and research such as *Horizon 2020*[1] which, among their basic objectives, propose that citizens become interested in science,

[1] Project promoted by the European Union that is available at https://ec.europa.eu/programmes/horizon2020/en/h2020-section/science-and-society

and actively, critically, and responsibly interact with the different agents and institutions that foster scientific and technological development. Logically, a good understanding of NOS will help these interactions to occur with more solid criteria and greater responsibility (Acevedo-Díaz & García-Carmona, 2017; Laherto et al., 2018).

However, the science education literature shows that often neither students nor their science teachers have a generally well-informed understanding of NOS (Lederman, 2007). In Spain, in addition to the sparse incidence of NOS in science classes at the different educational levels (Acevedo & García-Carmona, 2016a), explicit allusions to NOS in the school science curricula are minimal and clearly improvable (Acevedo-Díaz et al., 2017).

Given this situation, it is necessary to give an impulse to teaching proposals that encourage the introduction of basic NOS notions from early educational levels onwards (Akerson et al., 2011). This should be accompanied by specific teacher training plans at these levels (Hanuscin et al., 2011) aimed at improving prospective teachers' understanding of NOS (Akerson et al., 2006; García-Carmona & Acevedo, 2016). For prospective primary teachers (PETs) in particular, these training plans must also ensure that the PETs acquire the necessary self-efficacy to be able to apply NOS content in their own science classes (Bilican & Cakıroglu, 2011). To this end, designs have been suggested representing realistic educational proposals without any overly ambitious objectives so as to facilitate the integration of NOS content into the normal development of science classes (Acevedo-Díaz et al., 2017; Matthews, 2012).

The author and his research colleagues have for some time been developing specific educational proposals to train prospective science teachers in the understanding of NOS by using examples from the history of science (HOS). Use is made of self-elaborated short narratives (Acevedo-Díaz & García-Carmona, 2017) which, after being read by the learners, motivate their reflection and debate about some NOS issues that are contextualized in the content of each narrative. The purpose of this article is to present a qualitative and interpretative study focused on evaluating the educational effectiveness of an activity implemented with PETs for them to learn about some aspects of NOS in the context of the historical case of the discovery of the molecular structure of DNA, and Rosalind Franklin's role in it.

Research Questions

The research questions that guided the study were the following:

1. What are PETs' ideas about certain aspects of NOS following a first reflective reading of the historical case of Rosalind Franklin and the elucidation of the structure of DNA?
2. What is the progression of those ideas after the feedback the PETs received in a critical discussion of the case with their classmates and the educator?

The Nature of Science in Science Education

What to teach about the nature of science

NOS can be regarded as meta-knowledge about science that arises from interdisciplinary reflections made from the perspectives of the philosophy, history, and sociology of science. But what to teach about NOS? The response to this question is not simple when it comes to making a didactic transposition of this meta-knowledge, which is so broad and multifaceted, for its effective integration into the school science curriculum. Indeed, on the one hand, the aspects of NOS that may be more interesting, representative, and/or viable for scientific literacy at each educational level have to be selected, and, on the other, the degree of approximation or depth with which these aspects need to be addressed at each of those levels must be determined. Consequently, one is faced with a complex and controversial issue that is still the subject of a heated debate within the international science education community (Acevedo & García-Carmona, 2016a; Clough, 2018; Dagher & Erduran, 2016; Kampourakis, 2016; Wallace, 2017).

During the last few decades, some specific proposals have been made about which NOS aspects should be taught at non-university education levels (e.g., Lederman, 2007; Osborne et al., 2003; McComas, 2004). These proposals focus predominantly on the understanding of epistemic aspects of science, i.e., cognitive and rational aspects related to the construction and establishment of scientific knowledge (differences between scientific law and theory, differences between observation and inference, that observations are pre-charged with theory, that scientific knowledge is tentative but durable, subjectivity in science, myth of the one scientific method, etc.). With this, the contextual, social and psychological aspects related to science and scientists (i.e., non-epistemic aspects of science) receive minimal or just secondary attention in the commonest NOS teaching proposals. For example, Lederman (2007) only dedicated one of his seven NOS principles to referring, in a fairly general way, to the social and cultural influences affecting the construction of scientific knowledge. Similarly, only one of eight core NOS ideas proposed by McComas (2004) is referred (and then just generically) to the influence of historical, social, and cultural factors in science.

However, the history, philosophy, and sociology of science show the palpable influence of multiple non-epistemic aspects in the development of science (Matthews, 2012). Consequently, understanding these aspects should receive similar attention in status and proportion to that of the epistemic aspects in the basic and holistic teaching of NOS (Acevedo-Díaz et al., 2017). Along this same line, Irzik and Nola (2014) proposed that the understanding of NOS should include science's social and institutional dimension, i.e., professional activities, certification and dissemination of scientific knowledge, scientific behaviour, social values, etc. Dagher and Erduran (2016) suggested adding social organizations and interactions, public power structures, and science funding to this dimension. Martins (2015) proposed that teaching about NOS should contain a historical and sociological axis that integrates the role of scientists and the scientific community, intersubjectivity, scientific communication, the moral, ethical, and political questions of science, as well as the social and historical influences.

In line with the above, a holistic teaching of NOS is proposed, which is based on an exhaustive review of the literature, and which covers epistemic and non-epistemic aspects of science in a balanced way (Acevedo-Díaz et al., 2017). The proposal is the following:

- *Epistemic aspects of NOS*: (i) the nature of science processes (influence of scientists' beliefs and skills on their research, models and modeling in science, observation versus inference, the role of questions and hypotheses in science, the role of error in science, relationships between research designs and experimental results, diversity of scientific methods, scientists' creativity, etc.); and (ii) the nature of scientific knowledge (differences between scientific laws and theories, tentativeness of scientific theories, etc.).

- *Non-epistemic aspects of NOS*: (i) factors internal to the scientific community (role of scientific communication, scientists' personality, the role of the scientific community in the acceptance of scientific theories, scientists' rhetorical skills, scientific collaboration and cooperation, the influence of gender in science, etc.); and (ii) factors external to the scientific community (political, economic and cultural influences in science – and vice versa, science and religion, the media's role in disseminating science, etc.).

The educational viability of this NOS content proposal has proved itself successful in Secondary Education (with students aged 14 to 18 years) and in the training of prospective secondary science teachers (e.g., Aragón-Méndez et al., 2016, 2019; García-Carmona & Acevedo, 2017). That NOS content proposal has therefore been taken as the reference framework for the present study, selecting from it some epistemic and non-epistemic aspects to be discussed in the context of the activity analysed.

How to teach about the Nature of Science: Using the History of Science

There is considerable agreement that the teaching of NOS should be addressed explicitly and with a reflective approach (Abd-El-Khalick, 2012; Acevedo & García-Carmona, 2016a; Clough, 2011, 2018; Lederman, 2007). This means that NOS should be conceived of as specific curricular content, whose development in science class requires: (i) a teaching plan with its own learning objectives; (ii) the design of activities aimed at getting the students to think about and discuss reflectively the aspects of NOS; and (iii) an appropriate evaluation process to determine the degree of comprehension achieved by the students, detect their learning difficulties, and determine the necessary feedback to help them improve their understanding of NOS.

The teaching of NOS can be planned in an integrated way together with other school science content (e.g., Michel & Neumann, 2016), as independent content de-contextualized from that other content (e.g., Lederman & Abd-El-Khalick, 1998), or as a combination of the two strategies (e.g., Akerson & Donnelly, 2010). Some studies indicate that students tend to improve their understanding of NOS independently of the strategy used (Khishfe & Lederman, 2007). Even so, the integration of NOS with other content of the curriculum could serve as a stimulus for the science teaching staff to decide to deal with it in their classes without having to greatly alter the attention they pay to the other science content (Bell et al., 2012).

In addition to the above, it is recommendable to select specific context that helps the students to recognize, reflect on, and discuss certain aspects of NOS so as to improve their understanding of those aspects. In this sense, the reflective and critical analysis of controversial episodes in HOS is a context of especial interest (Allchin, 2011; Clough, 2011).

Teaching the Nature of Science through the History of Science. The use of HOS to teach NOS is ideal in order to contextualize and reflect critically on how scientists from different eras faced the challenges of their research, what role the scientific community played in the construction of scientific ideas, what influence the social, political, economic, and cultural contexts had, etc. (Acevedo-Díaz & García-Carmona, 2017; Clough, 2011; Irwin, 2000; Matthews, 2015; Rudge & Howe, 2009). Therefore, the use of HOS allows an imbricate approach to addressing epistemological, ontological, and sociological questions in science, thus favouring understanding of the epistemic and non-epistemic factors of NOS (Acevedo-Díaz et al., 2017; Justi & Mendonça, 2016).

The meditated reading of HOS case narratives together with reflection on and critical discussion about the NOS issues contextualized in them is a useful resource with which to introduce NOS into science education (Acevedo-Díaz et al., 2017; Irwin, 2000; McComas, 2008). There have been certain recommendations put forward for using HOS to learn about NOS: (i) make a didactic adaptation of the narrative, selecting and simplifying fragments and historical facts, but taking care not to end up with a pseudohistory (Allchin, 2004); (ii) avoid an idealized or mythical vision of science and scientists (Allchin, 2003); (iii) not omit scientists' mistakes and failures (Allchin 2003); (iv) incorporate scientists' own words so as to highlight the human side of science and thus add authenticity to the aspects of NOS they illustrate (Clough, 2011); and (v) not to make an anachronistic interpretation of the past which transmits a false cumulative and linear vision of science as being in continuous progression, but to show it in the reality of the historical-social context of the moment (Monk & Osborne, 1997).

Several studies have analysed the effectiveness of using HOS to learn about NOS in the initial training of science teachers. For example, Vallverdú and Izquierdo (2010) used the controversy between Pasteur and Pouchet about spontaneous generation to reflect with prospective secondary science teachers on errors in scientific research, conflicts of interest, citizen participation, etc. The results showed that the participants were able to partially appreciate the importance of debate and argumentation in the construction of scientific knowledge, as well as the influence of extra-scientific (non-epistemic) factors.

García-Carmona and Acevedo (2017) used a HOS narrative of the controversy between Pasteur and Liebig about fermentation to introduce prospective secondary science teachers to aspects of NOS that were both epistemic (e.g., the concept of scientific theory, differences in scientific interpretations of the same phenomenon, the role of error in science, etc.) and non-epistemic (e.g., influence of contextual factors in the development of science, the role of controversies among scientists, etc.). The participants improved their understanding of most of the aspects addressed. Satisfactory results were also obtained with a narrative about the case of Semmelweis and puerperal fever applied in a course for prospective secondary science teachers (Aragón-Méndez, 2019), in which numerous aspects, again both epistemic (e.g., differences between hypothesis and theory, influence of the procedures followed on the findings of scientific research, etc.) and non-epistemic (e.g., influence of the scientists' personalities, influence of politics on the construction of science, the role of scientific communication, etc.), were addressed.

Adúriz-Bravo and Izquierdo (2009) used a film about the discovery of radium by the Curies in order to introduce their prospective science teachers to the difference between discovery and invention, the role of scientific modeling, and the influence of gender in science. In general, the participants improved their views on these aspects.

Rudge et al. (2014) used a historical narrative about industrial melanism in their initial training of primary teachers to deal with epistemic aspects of NOS. The participants analysed a mysterious phenomenon presented as a puzzle, whose solution involved making use of certain pieces of knowledge about NOS. The participants mainly improved their understanding of the empirical nature of science. In the same vein, Williams and Rudge (2016) implemented a unit based on the history of genetics, taking an explicit and reflective approach, for the PETs to learn about NOS. The participants improved their understanding of the role of observation, inference, and culture in the construction of science.

Finally, Justi and Mendonça (2016) experimented with prospective chemistry teachers a dramatization activity about the controversial award of the Nobel Prize in Chemistry to Fritz Haber in 1918. The objective was essentially to improve their understanding of non-epistemic aspects of science and of skills in argumentation. In general, the results were positive, and, although the participants found it hard to elaborate quality arguments, their understanding improved thanks to the collaborative work they did during the activity.

METHODS

Context and participants

The participants in the study were 42 PETs (85.7% women and 14.3% men) of ages from 20 to 32 years (average: 20.8 years). They were being taught by the author of this study as a subgroup in the subject of Science Teaching (90 teaching hours). The subject is part of the second year of the Degree in Primary Education at a Spanish University. The participants therefore constituted a convenience sample.

The general objectives of the subject are for the PETs to: (i) reflect on and understand the purpose of basic science education; (ii) become familiar with the school science curriculum for Primary Education; (iii) know the students' conceptions and difficulties that are usual when they learn science; (iv) know the resources and strategies for teaching and evaluating science; and (v) learn to design science teaching units.

Most of the participating PETs had reached the university degree course from an academic path that was unrelated to science. Also, their preference for teaching science in school was generally low, as is common among PETs in Spain (Bonil & Márquez, 2011; García-Carmona & Cruz-Guzmán, 2016), and indeed in other PET contexts (Appleton, 2008). Spanish PETs usually begin their science education training with insufficient scientific knowledge (García-Carmona et al., 2014; Oliva & Acevedo, 2005; Verdugo, Solaz-Portolés & Sanjosé, 2016), and little understanding of NOS (García-Carmona & Acevedo, 2016; Guisasola & Morentin, 2007). Therefore, as is also the case elsewhere (Appleton, 2008; Capps & Crawford, 2013; Newman et al., 2004), in Spain training PETs to teach science faces the challenge of improving both their pedagogical content knowledge and their knowledge of the scientific content (García-Carmona Cruz-Guzmán, 2016; Martín del Pozo et al., 2013).

During the first year of their course, the PETs receive instruction on the basics of science (150 teaching hours in total). This does not, however, include NOS content. Consequently, the PETs participating in the study began their training to teach science without having previously received explicit teaching about NOS. Because of this, the program of the subject Science Teaching includes a unit called '*What is science? Nature of Science in science education*' covering approximately 15 teaching hours. The unit aims to diagnose the ideas the PETs have about NOS, improve their basic understanding of it, and provide them with some strategies and educational resources to be able to teach NOS in Primary Education. The activity to be analysed here forms part of that unit, and is aimed at improving the PETs' ideas about several epistemic and non-epistemic aspects of NOS.

Description of the activity

The activity consisted in reading a narrative elaborated by Acevedo and García-Carmona (2016b) about Rosalind Franklin and the elucidation of the structure of DNA, followed by a critical and reflexive discussion about various NOS issues (see Table 1) identifiable in the narrative. The narrative had already been implemented and validated with students of 17-18 years in age and with prospective secondary science teachers (Acevedo-Díaz et al., 2017). The following paragraph gives a brief summary of it.

Table 1
Questions proposed for reflection on aspects of NOS that arise in the narrative

Aspects of NOS	Questions for reflective discussion
Plurality of methods in scientific research	Q1. It is common to read the expression "the scientific method" as a universal, stage-by-stage process for the construction of scientific knowledge. According to what you have read, do you think this is adequate? Reason.
Objectives of scientific research	Q2. Do you think the objectives about DNA were the same for all the scientists involved? Do you consider that the objectives influenced the development of the research? Explain.
Strengths of the DNA model	Q3. What do you think are the main strengths of Watson and Crick's DNA model? Justify.
Epistemic and non-epistemic obstacles in scientific research	Q4. What epistemic factors (i.e., cognitive and rational aspects related to the construction and establishment of scientific knowledge) and non-epistemic factors (i.e., contextual, social, and psychological aspects related to science and scientists) do you think could have influenced Rosalind Franklin not being the first to elucidate the structure of DNA?

The elucidation of the molecular structure of DNA by James Watson and Francis Crick in 1953 was one of the great scientific discoveries of the 20th century. Together with Maurice Wilkins, they received the 1962 Nobel Prize in Physiology or Medicine for this. The mention said: "*for their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material*". In their acceptance speeches, the three laureates cited a total of 96 references, but none of these was to Rosalind Franklin, who had died in 1958, aged 38. Without forgetting the work of the Nobel laureates, the narrative deals with Franklin's important contributions to the elucidation of the structure of DNA through careful techniques of X-ray diffraction. The different goals of crystallographers and geneticists regarding the elucidation of the structure of DNA are set out, as well as the different methods they used – Franklin's being empirically based, and Watson and Crick's more theoretical through constructing hypothetical models. Likewise, other non-epistemic issues related to real scientific practice are brought out. One example is the tension and lack of collaboration between Franklin and Wilkins in contrast with the strong spirit of collaboration between Watson and Crick which gave rise to more fruitful scientific results. Others are the lack of ethics of Watson and Crick in using Franklin's data without her knowledge and without giving her due recognition, and the possible difficulties that Franklin had from being a woman in science at that time.

To implement the activity, the PETs were organized into small working groups of 3 or 4 members, for a total of 12 groups (G1 to G12). There were two reasons for this decision. The first was that the interaction between several individuals in a group usually leads to the elaboration of more complete responses because they have to agree on a common opinion that combines their different points of view (Salmerón, 2013). The second was that the PETs were already used to working in small groups in the Science Teaching subject, so that there would be no breach with their usual routine of organization and work in class. Even so, group work is not always easy. Therefore, as in the study of Sohr et al. (2018) concerning group work, during the activity the educator (i.e., the author of this study) laid especial emphasis on helping the members of each group being able to properly manage the agreements and disagreements that arose during discussion.

The activity was implemented in three phases:

i) *Initial phase: reading the narrative of the historical controversy and giving responses to the questions.* Without prior instruction, the PETs read the narrative and then responded as a group to the questions in Table 1. The educator encouraged each group to make their responses the result of an initial discussion and a consequent consensus among all the group's members. Nonetheless, the PETs were told that if opposing opinions emerged making consensus impossible, the different positions could be expressed in the response. The groups had to record these initial responses in a report. This first phase was carried out in a 2-hour class session, and allowed a diagnosis to be made of the PETs' initial ideas about the aspects of NOS being dealt with.

ii) *Intermediate phase: whole class discussion of the groups' initial responses to the questions about NOS.* After responding to the NOS questions they had been put, the groups shared and discussed their opinions in a class session of approximately 1.5 hours. The educator moderated the discussion between the groups and introduced clarifications, explanations, additional questions, etc. to enrich that discussion as much as possible. When the PETs expressed uninformed ideas about NOS, the educator tried to create a cognitive conflict so that they would reconsider their arguments. The purpose of this was for the groups to reach common conclusions about the different aspects of NOS being addressed, although without any indoctrination.

iii) *Final phase: the groups' conclusions after the whole class session.* After the discussion among the groups, each group had to revise, in a non-stressful manner, their initial responses, introducing the corrections, nuances, or extensions they considered necessary to improve their original arguments. To this end, they were allowed a deadline of somewhat longer than a week. The final responses emerging from this last revision were also recorded by the groups in their reports, following their initial responses. In this way, it was possible to assess any progression in the PETs' ideas about the NOS issues that had been discussed.

Data acquisition and analysis

The evaluation of the groups' responses to the NOS questions was done interpretatively, using the rubric presented in Table 2. This rubric was elaborated by the author and two research colleagues following the usual phases of qualitative content analysis (Mayrin, 2000). The rubric had been validated in two previous studies (Aragón-Méndez et al., 2016; Acevedo-Díaz et al., 2017). This details 5 levels of progression (from 0 to 4) for each NOS issue dealt with. The highest level (Level 4) corresponds to the fullest response in accordance with the level desirable for a basic understanding of the issue being alluded to in the narrative. The levels descend in terms of completeness down to the lowest level (Level 0) which corresponds to responses that are inadequate or do not refer to any of the features indicated in Level 4.

Table 2

Rubric for evaluating the aspects of NOS in the context of the case of Rosalind Franklin and the structure of DNA

NOS content	Level 4 (maximum)	Levels 3 – 0
Q1. Plurality of methods in scientific research	They explain that there is no one scientific method, and describe the two methods identifiable in the historical narrative: 1) Franklin's systematic empirical approach, and 2) Watson and Crick's elaboration of a functional model; likewise 3) they argue with reasons that neither method is per se better than the other, or that the two complement each other.	Level 3: They explain that there is no one scientific method, but (a) they only describe one of the two methods [1) or 2)], and argue that neither method is per se better than the other [3)] or that the two methods complement each other, or (b) they describe the two methods but without arguing that neither is per se better than the other. Level 2: They explain that there is no one scientific method, and give some justification (e.g., dependence on the researchers' interests or the characteristics of each research study); but they describe neither method [1) nor 2)], and they do not argue that neither of the two methods is per se better than the other or that the two methods complement each other [3)]. Level 1: They consider that several scientific methods are possible, but give no adequate justification. Level 0: They consider that there is only one valid scientific method.
Q2. Objectives of scientific research	They explain that the objectives were different, and in their explanation indicate three of the following reasons: 1) Franklin's objective is explained. 2) Watson and Crick's objective is explained. 3) The objectives are related to the scientists' training. 4) The objectives are related to the methods used. 5) The objectives are related to the priorities of the respective research centres.	Level 3: They explain that the objectives were different, and in the explanation they indicate two of the five reasons. Level 2: They explain that the objectives were different, and in the explanation they indicate one of the five reasons. Level 1. They explain that the objectives were different, but they do not provide any valid arguments. Level 0. They do not identify any

		significant differences between the objectives.
Q3. Strengths of Watson and Crick's DNA model	They indicate, in a justified way, at least three strengths. For example: 1) It explains the structure of DNA. 2) It allows explanations to be given and predictions to be made about the genetic code. 3) It allows a fertile hypothesis to be posited for future research. 4) It provides answers to multidisciplinary problems.	Level 3: They indicate two strengths in a justified manner. Level 2: They indicate one strength in a justified manner. Level 1: They indicate a strength but do not provide any justification or the justification is invalid. Level 0: They indicate no strength.
Q4. Epistemic and non-epistemic obstacles in scientific research	They indicate more than two factors, both epistemic and non-epistemic, with valid arguments. (i) Among the epistemic factors: a) The different objectives of Franklin's and of Watson and Crick's research. b) The methodological differences between the two investigations into the structure of DNA. c) The creativity shown by Watson and Crick in relating very diverse data. d) The researchers' training or area of expertise. (ii) Among the non-epistemic factors: a) Watson and Crick's lack of ethics in using Franklin's data without her knowledge or recognition. b) The tensions and lack of collaboration between Franklin and Wilkins versus the great spirit of collaboration shown by Watson and Crick. c) Watson and Crick's competitive nature. d) The possible difficulties that Franklin had because of being a woman in science at that time.	Level 3: They indicate with valid arguments at least one epistemic factor and one non-epistemic factor. Level 2: They indicate with valid arguments factors of only one type – either epistemic or non-epistemic. Level 1: They indicate with valid arguments one factor – either epistemic or non-epistemic. Level 0: They indicate no factors, or if they do then they give no valid arguments.

The categorization of the groups' responses followed a deductive procedure (Mayring, 2000). The author of this study was able to count on the collaboration of a research colleague in identifying the descriptors of the rubric in the groups' responses so as to assign those responses the corresponding level. For this, a method of analysis based on inter-rater agreement was used (Armstrong et al., 1997) in which the two raters evaluated the responses separately and then compared their categorizations. In cases of discrepancy, each rater revisited their categorization, and argued for it with the other rater in order to change or maintain their assignment. Up to three rounds of evaluation and discussion were necessary to reach full agreement in the categorization of some responses. The result of the process is summarized in Table 3. This contributed to providing the study with credibility, which is one of the essential quality criteria in qualitative research (Lincoln & Guba, 1985).

Table 3

Process followed in the categorization of responses by applying a method of inter-rater analysis

	1st round (% of agreement)		2nd round (% of agreement)		3rd round (% of agreement)	
Questions	Initial responses	Final responses	Initial responses	Final responses	Initial responses	Final responses
Q1	100%	87.5%		100%		

Q2	75.0%	75.0%	100%	83.3%	100%
Q3	91.7%	66.7%	100%	91.7%	100%
Q4	75.0%	66.7%	100%	91.7%	100%

To contribute to the confirmability of the study (i.e., the quality criterion equivalent to that of objectivity), the recommendations of Shenton (2004) of being careful that the data, interpretations, and conclusions were minimally biased by the researchers' opinions and beliefs were followed. To this end, the author's position as to what and how to teach about NOS has been stated above, as well as the rubric used in evaluating the PETs' responses to the NOS issues they were asked about. Likewise, the data were collected systematically, including with the use of low inference descriptors (Seale, 1999) consisting of excerpts of the groups' textual responses to the different questions.

Finally, with respect to the transferability of the results, strictly speaking they are not transferable because the sample, being one of convenience, is non-representative. Nonetheless, in accordance with Elliot (2000), this quality criterion was at least partially met in so far as the results of the study can be regarded as a source of reflection and guidance for other researchers considering similar qualitative research in their own specific contexts.

RESULTS

Recognition of the plurality of scientific research methods

Question 1 was intended for the PETs to distinguish and reflect on the two research methods that led to the elucidation of the molecular structure of DNA. On the one hand, Franklin's empirical method was aimed at obtaining X-ray diffraction images from which distances and bond angles could be inferred, thus allowing the structure of DNA to be determined. On the other hand, Watson and Crick's more theoretical method was aimed at constructing a hypothetical model of DNA's molecular structure from the experiments available. Watson and Crick were the first to reach a result, but Franklin was not far behind in solving the problem. Therefore, what was expected in this question was that the PETs would conclude that neither research method was per se better than the other, and consequently that the idea of a universal and algorithmic scientific method is a myth.

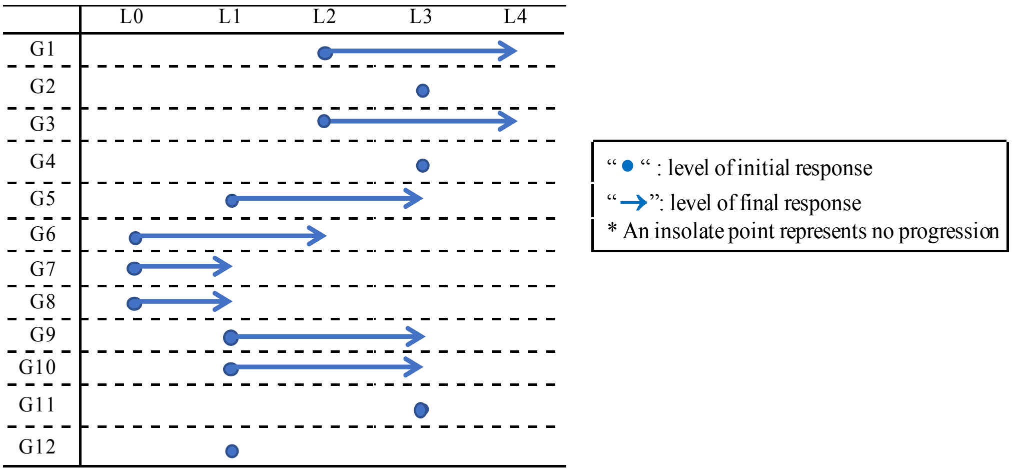

Figure 1. *The groups' progression on Q1: Scientific method*

Figure 1 shows the progression in level of the different groups' responses to Question 1. After a first reading of the narration (initial phase), a majority of groups (7 out of 12) gave responses categorized at the lowest levels (Levels 0 and 1), 2 groups at an intermediate level (Level 2), and 3 groups at a high level (Level 3); no group reached the maximum level of the rubric (Level 4). Three of the groups at the lower levels showed they had the idea that there is a unique scientific method or one that is more valid than others (Level 0). This was expressed by one of them:

> "[…] We believe that it is very important to carry out the steps that make up the scientific method, because for a good scientific construction it is essential to have a method based on systematic observation, measurement, experimentation, formulation, analysis, and modification of the hypothesis." (G8)

The four groups located at Level 1 practically limited themselves to saying that there is no single research method in science, without giving any adequate argument. For example:

> "[…] there is no universal scientific method for all experiments. Each experiment requires a series of steps to be carried out depending on its characteristics." (G5)

The two groups giving intermediate level initial responses (Level 2) delved a little deeper into the idea that there is no single scientific method. They alluded to the subjective nature of scientific research and, consequently, to the relevance of each method depending on the needs or approaches of the scientist. They did not, however, contextualize their arguments in terms of the narrative's content. One of the groups wrote the following:

> "[…] although there are established phases [in the scientific method] that function as a starting point, when carrying out a construction of scientific knowledge, each scientist will apply it in the way they believe to be most appropriate, making it have a subjective character, and more suited to their research. […]" (G1)

The three groups with the most elaborate initial responses (Level 3) addressed the above idea more broadly, in addition referring to the two methods expounded on in the narrative of the case. They did not explicitly allude, however, to the fact that the two methods can be considered complementary, or that neither of them was per se better than the other. One of these groups put it like this:

> "We believe that the scientific method is very useful and almost all scientists follow certain steps, but this is not universal, because each scientist follows their indications including nuances depending on the objectives that had been set. […] the purposes of the research that was being carried out at the Cavendish Centre and King's College were different. For Watson and Crick, the elucidation of the structure of DNA was not an end in itself, but a means to explain the genetic code and the transmission of genetic information. On the contrary, the main purpose of Franklin and Wilkins as crystallographers was to clarify the structure of DNA accurately from data obtained by X-ray diffraction." (G2)

The discussion among the groups during the whole class session (intermediate stage) led them to revise their initial responses. As a result, two-thirds of the groups achieved some progression in their ideas, and no group maintained the idea that there is a single unique method in scientific research. However, the groups that held this idea in the initial phase (G6, G7, and G8) achieved little progression (only from Level 0 to Levels 1 or 2) because they gave only weakly reasoned arguments in their responses. It is also noteworthy that five groups progressed in their ideas from low levels of understanding to high (Level 3: G5, G9, and G10) or very high (Level 4: G1 and G3) levels. For example, G1 went from Level 2 to Level 4 with the following final response in which they referred to the fact that the methods followed by the two groups of researchers in the narrative were different but complementary:

> "[…] after the debate carried out in class, we all agree that the scientific method is not universal; however, this is still talked about. Therefore, we are generating a distorted image of scientific research. A clear example to see that the same steps are not followed in scientific research can be found in the narrative. […] the objectives that are pursued are not the same and there appear two research groups using two different methods. Franklin's was based on experiments with X-rays, getting images with more quality. She was more systematic and based on experimentation. Watson and Crick based themselves on making structures, representations, and models. They achieved their objective thanks to their research together with what Franklin had discovered without being aware of it. Therefore, both had merit using different paths, because they ended up being complementary in some way." (G1)

Finally, it must be said that there were four groups that did not show any progression in their ideas. G12 remained at Level 1 because they failed to minimally argue the existence of a variety of methods in scientific research (Level 1). And the other three groups (G2, G4, and G11) remained at Level 3 because they continued to not explicitly integrate into their arguments that the research methods of Franklin and of Watson and Crick, as well as being different, were complementary in the elucidation of the structure of DNA (i.e., neither was per se better than the other).

Identification of the research objectives

The purpose of Question 2 was for the PETs to recognize that the objectives of the research done by Franklin and Wilkins and by Watson and Crick were different. Franklin and Wilkins only sought to determine the molecular structure of DNA by X-ray diffraction, while for Watson and Crick the elucidation of the structure of DNA was a means to achieving explanations of the genetic code and the transmission of genetic information. Therefore, it was expected that the PETs could relate this difference in research objectives to the different methods used by the two research groups, the academic training of the scientists involved, and the priorities of the research centres at which they worked, among other factors.

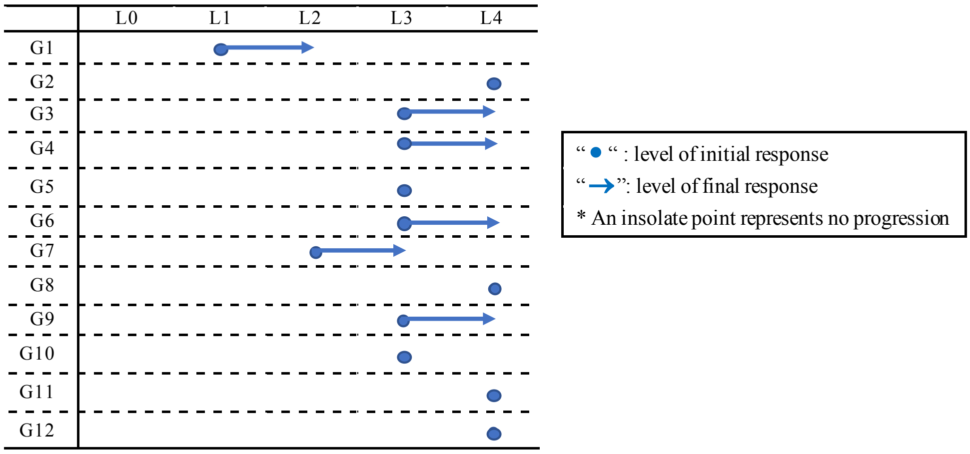

Figure 2. *The groups' progression on Q2: Research objectives*

The progression in levels of the groups' responses to Question 2 is shown in Figure 2. It is worth noting firstly that in the initial phase a majority of the groups gave responses categorized at the highest levels: six groups at Level 3, and four groups at Level 4. This highlights that the first reading of the narrative seems to have been quite clarifying for the PETs in relation to the content of this question. The following are examples of responses given by groups located at high levels from the beginning:

> "Each had a different objective and therefore their research methods were also very different. In the case of Watson and Crick, the elucidation of the structure of DNA was used as a means to explain the genetic code and the transmission of information. Whereas for Franklin and Wilkins it was to clarify the structure of DNA by X-ray diffraction. […] starting from different points, it is equally possible to reach the scientific knowledge being sought." (G6, Level 3)

> "No. On the one hand, Watson and Crick needed to know the structure of DNA, in order to later investigate their final objective, i.e., it was a path to do this. On the other hand, Franklin and Wilkins had as their final objective to know the structure of DNA. Therefore, the objectives were completely different, in one case it was just a path, and in the other it was the ultimate goal." (G10, Level 3)

> "The objectives were not the same, while R. Franklin wanted to go deeper into the internal structure of DNA simply to obtain that concrete knowledge, Watson and Crick sought a more overall view of the structure of DNA with more applicable objectives. For Franklin, precision based on numerous data was necessary for the construction of an adequate model [of the structure of DNA], whereas for Watson and Crick it was not and they saw this as a limitation. For them, the path was to establish an initial model that would become more sophisticated over time. These objectives clearly influenced the development of their research, because while Franklin was looking for the collection of concrete empirical data, Watson and Crick oriented their research to the collection of previous empirical data from other researchers for the final construction of the model." (G11, Level 4)

> "Yes, the objectives directly influence the development of the research, both in the method and in the importance given to certain aspects within the object studied. We can say that each scientist takes a different path depending on their interests and preferences. Specifically, in the narrative two research studies are expounded on, which, because of having different objectives although with common aspects, follow different paths: The objective of Franklin and Wilkins was to clarify the structure of DNA with precision, so they used a completely analytical method, based on the meticulous and accurate analysis of a large number of empirical data. On the contrary, the objective of Watson and Crick's research was to understand the genetic code and the transmission of genetic information. Because of this their research followed a more intuitive method, where the meticulous analysis of the data was not necessary, although they later confessed that they were aided by Rosalind Franklin's accurate reports and analyses." (G12, Level 4)

Only G1 gave a response categorized at a low level (Level 1) because, although it recognized that the objectives of both sets of researchers were different, it did not provide sufficiently valid arguments:

> "At first, yes, because the research about DNA had the same basic objective as a starting point: to know how DNA works and its structure. Despite this, as a result of the new knowledge, the objectives are not the same and they branch: some want to explain the transmission of the genetic code, others to clarify the structure of DNA. […] according to the objective established, the scientific method will be adapted in one way or another." (G1)

The remaining group (G7) was at an intermediate level (Level 2) in referring only to Watson and Crick's objective:

> "[…] for Watson and Crick, discovering the structure of DNA was not an end, but a means to obtain explanations about the genetic code and the transmission of information. Yes [the objectives influence the development of research] because if you want to reach a specific conclusion, you will only rely on tests and results that lead you towards your objective. Therefore, you may leave things behind, because you may ignore data that does not seem necessary, although it really is." (G7)

After the whole class session (intermediate phase), six of the eight groups that had some margin for improvement in their initial responses showed some progression (groups G5 and G10 remained at Level 3). Thus, at the end of the activity almost all the groups (11 out of 12) presented high levels of understanding (Levels 3 and 4). It is also worth noting that G1 managed to progress to at least an intermediate level (Level 2). In their final response, they mentioned the objectives of the two research processes, although they mistook the workers involved, and referred very sparingly to how different research objectives give rise to different research methods:

> "The objectives about DNA were not the same for all the scientists involved: while Franklin's objective was related to genetic transmission; Watson and Crick's objective was to clarify the structure of DNA. However, the objectives do influence the development of the research, because, depending on the objective that is set out, different research paths will be followed." (G1)

Identification of the strengths of Watson and Crick's model of the structure of DNA

Question 3 was focused on the PETs identifying the strengths of Watson and Crick's model of the molecular structure of DNA. These include that the model: allows the data then available to be interpreted, and fits these data well; explains the transmission of genetic information; makes predictions about the genetic code allows fertile hypotheses to be posited for future research; and gives an answer to multidisciplinary problems. Figure 3 shows the progression in level of the groups' responses to this question.

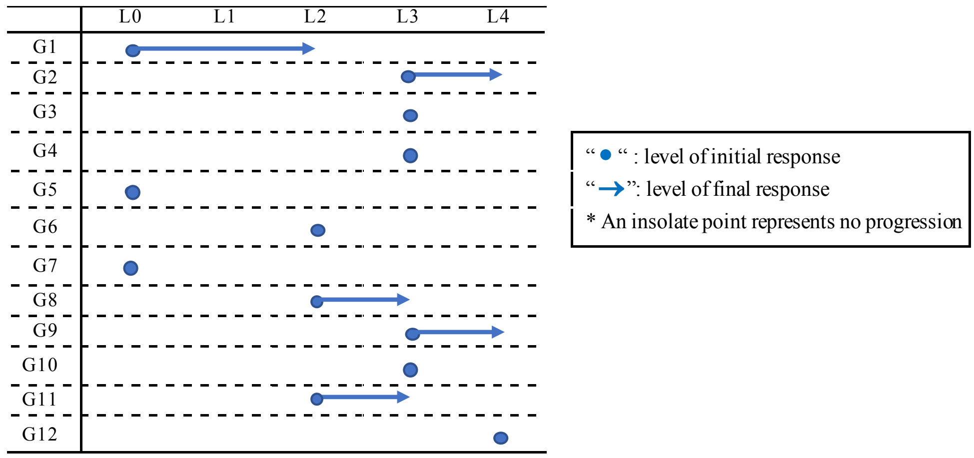

Figure 3. *The groups' progression on Q3: Strength of the DNA model*

In the first phase of the activity, three groups gave responses that did not make any allusion to any of the strengths of Watson and Crick's model (Level 0). For example:

> "Watson and Crick wanted to know the structure of DNA to explain the genetic code and genetic transmission. Their model consisted of working in the laboratory using collaborative methods, one gave an idea and the other debated it taking it seriously to try to reach agreement and be able to use that information. Because they did not have the purpose of deciphering the structure of DNA, like Franklin and Wilkins, they had more evidence on which to base themselves and from which to get more information, because Franklin worked with crystallographic techniques." (G7)

On the other hand, half of the groups gave initial responses that were categorized at the highest levels (5 at Level 3, and 1 at Level 4), outstanding being their allusions to the explanatory and predictive power of the model in relation to the structure of DNA and hereditary transfer. Two examples of responses by these groups are the following:

> "Watson and Crick elaborated their model with great creativity based on their own ideas, such as the pairing of nitrogenous bases, of great biological importance, and with DNA data provided by other researchers. The idea that the structure of DNA was a double helix was taken from Franklin's studies. Watson and Crick's model not only explained the structure of DNA, but also allowed for predictions to guide new research." (G4, Level 3)

> "One of the strengths of Watson and Crick's model is that it explained the structure of DNA, which allows predictions to be made to channel future research. It can also be noted that Watson and Crick developed their DNA model from the research that other scientists had done. Another of its positive aspects was the large amount of additional information it provides about the

> [DNA] structure. Likewise, it allows certain calculations to be done to determine the number of chains per molecule. Finally, and the most important, [it explains] the hereditary transmission of genetic information." (G12, Level 4)

The rest of the groups (3 out of 12) gave responses alluding to some of the strengths of Watson and Crick's model (Level 2). For example, G11 referred to the fact that the proposed model responded satisfactorily to the different questions that the researchers had asked themselves; and G8 focused its argument on the model's ability to explain the DNA molecule's structure:

> "The greatest strength of Watson and Crick's model is the integration of all the ideas and data that had been obtained to date into a single model, which also worked and made sense. […]." (G11)

> "[…] Watson and Crick elaborated their model with great creativity based on their own ideas, such as the pairing of nitrogenous bases, of great biological importance, together with data provided by other researchers. Pauling's three-dimensional models were their main source of inspiration when deciding the sizes, shapes, and spatial arrangement of the subunits that make up DNA molecules. […]" (G8)

After the intermediate phase of presentation and discussion of their initial responses in the whole class session, five groups (G1, G2, G8, G9, and G11) achieved some progression in their final responses, although it is worth remembering that half of the groups had already reached high levels (Levels 3 or 4) in their initial responses. Only G5 and G7 remained at a very low level of understanding after this whole class session.

Among the groups that progressed, there stands out G1 which went from Level 0 to Level 2 in alluding in their final response to the fact that Watson and Crick's model was useful as a foundation for answers to the research questions that geneticists were tackling about DNA:

> "Watson and Crick formed a very detailed model, which helped them to convince others that everything they said was correct. The most important thing is that the said model responded to the questions that were being asked and contributed to new knowledge. […]" (G1)

Of the other groups that progressed, it shall be quoted as an example a fragment of the response with which G2 went from Level 3 to Level 4:

> "Watson and Crick's model not only explained the structure of DNA, but also allowed predictions that could guide future research. Watson and Crick had deciphered the structure of DNA. It is a very detailed model that does not give rise to doubts and answered most of the questions that were being asked." (G2)

Epistemic and non-epistemic factors that conditioned Rosalind Franklin's research

Question 4 was intended for the PETs to reflect on and discuss epistemic and non-epistemic factors that determined the outcome of research on elucidating the molecular structure of DNA. They were especially expected to detect the obstacles that might have prevented Rosalind Franklin from successfully completing her research. As epistemic factors, the following stand out: the different objective of Franklin's research relative to that of Watson and Crick; the methodological differences between the two groups of researchers; the creativity of Watson and

Crick in relating very diverse data; and the different training and areas of specialization of the researchers involved. The following are non-epistemic factors that can be found as converging in this case: Watson and Crick's lack of ethics when they used Franklin's data without her knowledge or subsequent recognition; the tensions and lack of collaboration between Franklin and Wilkins versus the great spirit of collaboration shown by Watson and Crick; Watson and Crick's competitive nature; and the possible difficulties that Franklin faced at that time from being a woman. The PETs' responses were considered to be at the highest level of understanding if they alluded to at least two of the epistemic and two of the non-epistemic factors mentioned above.

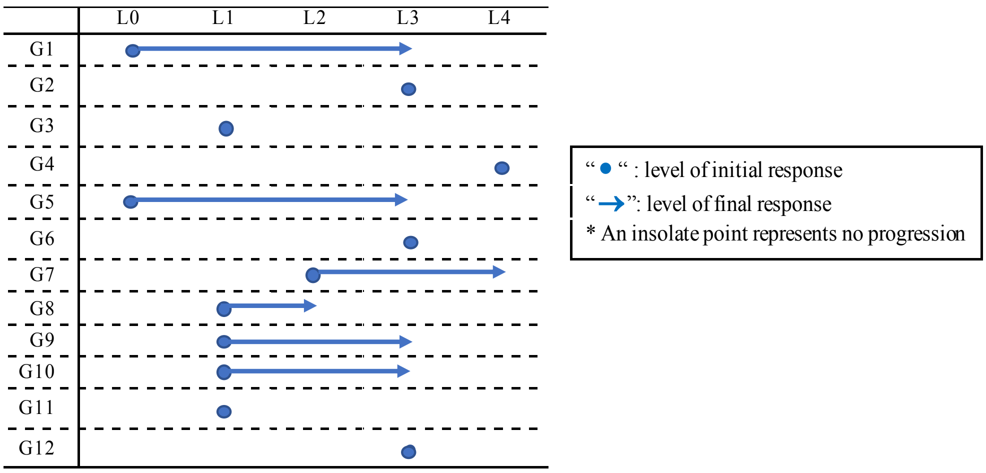

Figure 4. *The groups' progression on Q4: Epistemic and non-epistemic obstacles*

The results on this question are shown in Figure 4. As can be seen, the majority of the groups (7 out of 12) gave initial responses categorized at the lowest levels (Levels 0 and 1). In these responses it was observed that the groups' identification of the two types of factor (i.e., epistemic and non-epistemic) in the narrative was either sparse or inadequately argued. The following is an example of a response in which the two types of factor were presented with uninformed arguments (G5, Level 0):

> "- Epistemic factors: Franklin thought that the structure of DNA had an A and B form, which took her a long time of research. In contrast, Watson, from a photograph, clearly observed the B form. Watson and Crick also received more help and took into account the information others had gathered.
> - Non-epistemic factors: The condition of being a woman, and the little help she received, unlike Watson and Crick who used her research not to complement hers but for them to enjoy the merit." (G5)

Another example of an initial low-level response was given by G9. It only adequately justified the non-epistemic factor related to Franklin's condition as a woman scientist (Level 1):

> "[…] Franklin's gender was a stigma in her life as a scientist because at that time there was a reality where the male gender predominated in all the fields of knowledge. No woman was taken into account when making contributions in those fields." (G9)

G7 was the only group initially situated at an intermediate level (Level 2) because they justified two non-epistemic factors (Franklin's difficulties due to being a woman, and her bad professional relationship with Wilkins):

> "[…] Rosalind Franklin was a woman and therefore not taken seriously. She did not have as much help, what she had done was not even recognized as being good and helping to reach an objective. She did not get on with her partner [Wilkins], so they did not work [well] as a team. […]." (G7)

It should also be noted that the initial responses of some groups included inaccurate or erroneous interpretations. For example, that "*[...] The methods of the other researchers [Watson and Crick] were more based on trial and error*" (G9), or that "*[...] Watson and Crick plagiarized Franklin's work*" (G2). Also, there were overly drastic statements in the responses of some groups that in no way had been transmitted in the narrative. For example: "*[...] No woman was taken into account when making contributions in these fields [of scientific research].*" (G9).

At the highest initial response levels, there were five groups at Level 3, and one at Level 4. Examples of the responses of these levels are the following:

> "When analysing the epistemic factors the most significant is the method used in the research. She [Franklin] was absolutely analytical, because her objective was the clarification of the structure of DNA. To do this she needed a meticulous and accurate analysis of a large number of empirical data, which would mean a large amount of time that she could not devote to other crucial aspects to be able to complete her study. The non-epistemic factors […], the chauvinism of that time underestimated women and defined them as individuals inferior to men. This fact considerably damaged Rosalind Franklin. However, we believe that the most significant factor was the enmity between Franklin and Wilkins, which markedly stagnated the research and delayed its publication. In addition, when Franklin took on, involuntarily, the position of Wilkins' subordinate, she could not work in a free and autonomous manner." (G12, Level 3)

> "Regarding the epistemic factors, we would highlight the following: 1) different objectives in Franklin's and in Watson and Crick's research; 2) their methods were different; Franklin used an empirical method, despite its drawbacks, which gave her greater security in her […] inferences about the structure of DNA; 3) the creativity of Watson and Crick regarding the relationship of their own and other people's data. On the other hand, the non-epistemic factors that we find are the following: 1) [greater] competitiveness of Watson and Crick; 2) the lack of ethics of Watson and Crick for using Franklin's data without prior consent; and 3) difficulties that confronted Franklin [in her scientific research] due to being a woman." (G4, Level 4)

Once the intermediate phase of whole class sharing and discussion had concluded, six groups showed some progression in their final responses. The most outstanding progressions were those achieved by G1 and G5 who went from Level 0 to Level 3 in significantly improving their initial arguments. For example, G5 achieved this with the following response:

> "- Epistemic factors: […] Watson and Crick did not pursue the same objective. Rosalind only based herself on "the photo" [Photograph 51]; however, the others [Watson and Crick] investigated other aspects from that photo. Rosalind was more creative and improved her own crystallographic analysis processes. […]

- Non-epistemic factors: Given her condition of woman [Franklin], her research was not given the same importance, and she received little help unlike Watson and Crick who used her research not to complement hers but for them to enjoy the merit, and there was an absolute lack of ethics. Also, they had a better relationship [than Franklin and Wilkins]." (G5)

Groups G9 and G10 also improved their understanding, going from a low level (Level 1) to a high level (Level 3) by adding to their respective responses the citation of an epistemic obstacle to Franklin's research. G10 explained it in the following way:

"- Epistemic: Franklin focused on getting the best picture [of the supposed structure of DNA], but it was Watson and Crick who knew how to interpret it and give it meaning. They were creative and able to take their own studies and join them with data from other studies to reach their objective. […] Creativity is key in scientific studies, having ideas, tests to carry it out.
- Non-epistemic: Franklin's bad relationship with her partner Wilkins, as he considered her to be an assistant who helped him in his research and not as a work colleague, because she was a woman, despite her scientific recognition. Therefore, there was a lot of competition between them and they did not work well as a team. Watson and Crick were able to argue with each other constructively to expand their knowledge, ideas, and be able to integrate them all. That Franklin was a woman also had an influence, and at that time she was not so well recognized. There was a great lack of ethics, and then in the 1990s they were forced to recognize Franklin's fundamental work." (G10)

Also, worth noting is the progression of G7 from an intermediate level (Level 2) to the highest level (Level 4). As shown above, this group only alluded to two non-epistemic obstacles in their initial response, but at the end of the activity they incorporated into their arguments a non-epistemic obstacle (Watson and Crick's lack of ethics) and three epistemic obstacles (different research objectives, and different methods, and Watson and Crick's greater creativity in relating data):

"- Non-epistemic: (i) That Rosalind Franklin was a woman and therefore she was not taken seriously. She did not have so much help, so it was not recognized that much of what she had done was good and was helping to reach an end. She did not get on with her partner [Wilkins], so they did not work [well] as a team. […] (ii) Watson and Crick's lack of ethics, because she was helping them, while they were taking and using her information without her knowledge.
- Epistemic: (i) [Franklin] focused too much on getting to know the structure of DNA via only one path and leaving untouched a lot of useful information. Franklin was too detailed and careful, so she paid attention to every detail, even if it was very small, which made her take more time […]. (ii) The two teams did not have the same objectives. (iii) […] Watson and Crick were creative because they knew how to use information from various people and places in order to achieve their objectives. So we can verify that without creativity nothing is achieved." (G7)

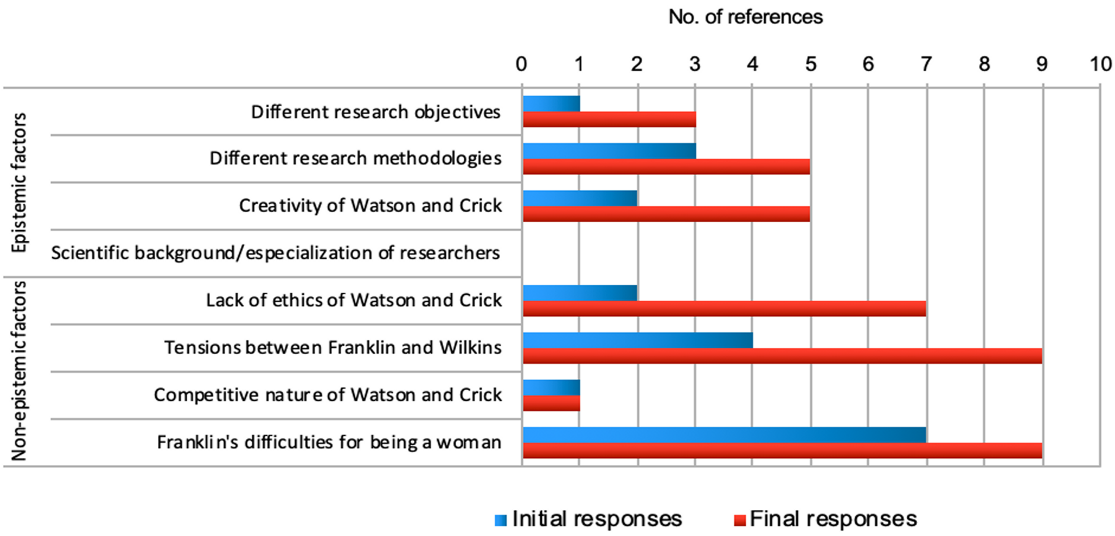

Figure 5. *Epistemic and non-epistemic factors cited in the groups' responses to Q4*

An analysis was also made of the number of epistemic and non-epistemic factors that were alluded to by the groups in their responses, and the progression of these allusions from the initial to the final phases of the activity. The results are detailed in Figure 5. As can be seen, the epistemic factor related to the influence of the scientists' background or specialization in the development of their research was not mentioned in any of the groups' responses. References to the different epistemic and non-epistemic factors, except that concerning Watson and Crick's competitive nature, increased throughout the activity. In this regard, the allusions to non-epistemic factors were, from the beginning, far more numerous than those to epistemic factors – specifically, they were twice as frequent: 14 versus 7 in the initial responses, and 26 versus 13 in the final responses. The greatest increase in these references corresponded to two non-epistemic factors: Watson and Crick's lack of ethics, and the professional tensions between Franklin and Wilkins. This last factor, together with Franklin's difficulties in her research due to being a woman, were the two most cited factors in the groups' responses right from the beginning of the activity.

With respect to the epistemic factors, the most cited from the beginning of the activity were the influence of different research methods, and Watson and Crick's creativity as being determinants for these last two workers to reach the goal of the research before Franklin.

Discussion

According to the results, and from an overall perspective, it can be said that a critical and reflective reading of the historical case on the elucidation of the molecular structure of DNA significantly helped the PETs to express and improve their conceptions about the aspects of NOS discussed in the activity. This is consistent with the findings of other studies that also used HOS to learn and teach about NOS (e.g., Adúriz-Bravo & Izquierdo, 2009; García-Carmona & Acevedo, 2017; Rudge & Howe, 2009).

Regarding the first research question, the initial phase of the activity allowed us to determine the PETs' initial ideas about the aspects of NOS that were dealt with, and the quality of their arguments in defence of such ideas. Thus, at the beginning it was found that around a quarter of the PETs considered that there is a standard or universal research method which all scientists use for their research. This therefore was an example of an inadequate conception coming to light, one deeply rooted in both science teachers and their students (Lederman, 2007). But also notable in this first phase was the difficulty that a considerable proportion of the PETs had in arguing that scientists usually apply a variety of methods during their research. In accordance with the findings of Justi & Mendonça (2016), this might be due to the fact that, after the first reading, the PETs did not understand the content of the controversy with respect to that aspect. This would not be surprising considering the PETs' sparse scientific background, as was described above.

With its first reading, the narrative of this historical case was effective for the great majority of the PETs to become aware that different research objectives often lead to different methods or approaches to that research. This effectiveness of a historical narrative in improving understanding of this non-epistemic aspect of NOS has also been confirmed in studies with both students and prospective science teachers of Secondary Education (Acevedo-Díaz et al., 2017). It should be mentioned that this is an aspect of NOS that has scarcely at all been analysed in the literature. The author of this study considers, however, attention to it in teaching NOS is important not only because it is a basic aspect of NOS, but also because its reflective analysis, together with the appropriate feedback and scaffolding, can help progress towards the abandonment of the idea that there is a unique and universal scientific method.

Regarding the understanding that PETs have about the nature of scientific models, the analysis carried out is also relatively novel. Students' and teachers' conceptions about the meaning and role of models in science have usually been diagnosed through tests consisting of generic and de-contextualized questions (e.g., Lin, 2014; Treagust et al., 2002). Instead, the focus in the present study was on reflection about a specific scientific model – that developed by Watson and Crick for DNA. The intention was for the PETs to be able to comprehensively identify in the historical account the characteristics of this model that were most relevant for its acceptance by the scientific community. In the initial responses, most of the PETs indeed referred to some characteristic feature of Watson and Crick's model, but few referred to various of these features in the same response (e.g., the explanatory and predictive power of the model, its fit to the available empirical data, etc.). Therefore, the initial discussion of the question related to scientific models found that, rather than inappropriate conceptions, the PETs had incomplete or poorly argued conceptions about the characteristics that a model must have to be accepted by the scientific community.

In relation to the identification of epistemic and non-epistemic obstacles that could have interfered in Franklin's research, at the beginning, half of the PET groups either referred to just a small number of obstacles or these obstacles were presented with poor or inappropriate arguments. A similar difficulty had been found by Aragón-Méndez et al. (2019) in proposing to prospective secondary school science teachers that, in a narrative of the historical case of Semmelweis and puerperal fever, they might identify the epistemic and non-epistemic obstacles that this scientist faced for his hypothesis to be accepted. Perhaps this is a consequence of the prospective teachers not being used to analysing aspects of NOS, and even less to discussing them, even if they have a sufficient scientific background (Justi & Mendonça, 2016).

Also, in the groups' initial responses, references to non-epistemic factors exceeded those to epistemic factors. The non-epistemic aspect most cited was that referring to the difficulties that Franklin had because of being a woman at a time when women had little visibility in science compared to men. However, in some cases this was done with arguments that were too drastic (e.g., "at that time, no scientific woman was taken into account in research studies"). Possibly this was because the PETs were interpreting a past event with the criteria of today; i.e., a *whig* view of HOS (Allchin, 2004).

Regarding the epistemic obstacles, the one most cited in the initial responses was that the use of a different method by each research team was decisive for one of them (Watson and Crick) to be able to decipher the structure of DNA before the other (Franklin and Wilkins). However, even this was alluded to in only a small portion of the responses. This is understandable from the results for the first question which showed the initial difficulties the PETs had in accepting and/or arguing well for the plurality of methods in scientific research. One group identified the modeling and testing process that Watson and Crick followed with a procedure based on trial and error. This type of naive conception was also observed in another study on the understanding of aspects of NOS using HOS (García-Carmona & Acevedo, 2017).

With respect to the second research question, it stands out that, after the whole class session of sharing and discussion, the conceptions and arguments about the aspects of NOS dealt with improved to some degree in most groups. The clarifications introduced, the discussions among the groups to achieve agreements regarding the NOS issues analysed as well as the auxiliary questions, which are asked by the educator to generate cognitive conflict when PETs expressed incomplete or limited ideas, were crucial in this improvement. As in other similar studies (e.g., García-Carmona & Acevedo, 2017; Aragón-Méndez et al., 2019; Williams & Rudge, 2016), this therefore reveals the importance of the feedback received from the other groups and the educator in enriching each group's own arguments. At the end of the activity, about three-quarters of the groups responded to all the questions with statements that were categorized at the highest levels in accordance with the evaluation rubric used. In this last phase, no group expressed the idea that there is a unique and universal scientific method, and most of them stated with appropriate arguments that the same research problem could be approached using different methods. Also, one of the most frequently cited epistemic aspects was how the fact that Franklin used a different research method from that of Watson and Crick could have conditioned her not elucidating the structure of DNA before them.

At the end of the activity, most of the groups of PETs had also improved their understanding of Watson and Crick's model as expressed in their richer arguments concerning the relevant characteristics of the model. A recent study by Gogolin and Krüger (2018) showed that students' understanding of the nature of scientific models depends on the specific contexts in which they are introduced in class. An essential task for science teachers should therefore be to focus on choosing the most appropriate contexts for their students to improve their understanding of the nature of models. In this sense, one can say that the activity analysed in the present study used a context (the elucidation of the molecular structure of DNA) that is effective for learning about the nature of scientific models.

Similarly, it is worth noting that the PETs ended up becoming aware of a greater number of epistemic and non-epistemic factors that could have hindered Franklin's research from achieving her objective of elucidating the structure of DNA. Nonetheless, the identification of non-epistemic factors continued to be manifestly more frequent than that of epistemic factors. The two non-epistemic aspects most cited at the end, and with some difference from the others, continued to be Franklin's difficulty due to her being a woman, and the tensions between Franklin and Wilkins in working together. Therefore, it can be said that the reading and discussion of the historical narrative was effective for reflection on the gender bias that usually exists when recounting how science has been constructed throughout history (Adúriz-Bravo & Izquierdo, 2009).

In general, in their reflections the PETs gave great importance to the influence of non-epistemic factors in the scientific research that was being analysed. This should make educators who undervalue the inclusion of non-epistemic as against epistemic aspects in their teaching of NOS reflect seriously on the relative value they give to the two.

Limitations of the study and perspectives

As just noted above, the results of the study were in general quite satisfactory. However, the fact that they were obtained through a short-term intervention suggests questioning the extent to which the levels of understanding achieved by the PETs reflects a meaningful assimilation of the aspects of NOS that were dealt with. In this sense, it would have been interesting if, after some time, the PETs returned to reflecting about these aspects of NOS, e.g., in the context of another case of HOS or of contemporary science. However, the activity was implemented within the real possibilities and circumstances that existed of teaching time and programming. Even so, it should be noted that longer teaching interventions aimed at learning about NOS using HOS (e.g., Abd-El-Khalick & Lederman, 2000) have not been shown to be much more effective than the present one. This is perhaps because "*evaluating course length interventions may introduce noise that masks the effects of historical instructional approaches*" (Williams & Rudge, 2014, p. 442). Consequently, the author of this study agrees with Rudge et al. (2014) that a short teaching intervention, such as the one analysed here, which takes place under normal class conditions can be quite effective in getting some improvement in the students' understanding of NOS.

Another possible limitation of the study is related to the fact that the responses to the NOS questions were elaborated as a group. In this regard, one might ask, for example, whether the responses of each group really represented the opinion of each and every member of the group, or rather prevalently those of the member of the group with the greatest capacity for dialectics or conviction. Be that as it may, the broad experience of the educator in promoting reflexive discussions in small groups for the entire class to learn about and diagnose ideas about NOS (e.g., García-Carmona & Acevedo, 2016, 2017) was essential in order to minimize this possible limitation. As was advanced above, and in line with the approach of Sohr et al. (2018), the educator provided encouragement to all the groups, insistently and with the appropriate scaffolding, so that their responses should emerge from discussion and consensus among all the members. They were also assured that, when consensus was impossible, their different opinions were to be expressed in the group's response (although this did not actually occur in any case in the present activity).

Regarding the intermediate phase of the activity (i.e., whole class discussion of the groups' initial responses), although this was key to improve the PETs' ideas about the NOS aspects dealt with, it was indirectly analysed in this study. Therefore, in order to deepen on how this phase specifically contributes in such improvement, the discussions among the PETs during the whole class session should also be analysed in next implementations of the activity.

In addition, as was mentioned in Methods, the fact that the study was carried out with a convenience sample prevents the present results and conclusions being considered as transferable to the entire population of Spanish or any other PETs. Nonetheless, in agreement with Elliot (2000), these results and conclusions can be considered as constituting an important source of reflection and guidance for other studies that may be planned in similar contexts and circumstances.

Having said all this, as a summary it can be said the activity presented constitutes a suitable and effective resource to learn about some basic aspects of NOS in initial elementary teacher education. In fact, the activity is easily adaptable to usual class conditions (2-3 class sessions are only necessary for its implementation), and it allows the educator (a) to diagnose the PETs' NOS ideas in the context of a specific HOS case, (b) to promote among the PETs a critical and reflective discussion on NOS aspects, and (c) to assess learning progressions on the PETs' understanding of NOS from an interpretative approach through an assessment rubric designed specifically for this.

Finally, it is important to note that this study only focused on investigating how the critical and reflective analysis of a HOS case can help improve the PETs' understanding about some aspects of NOS. In this way, the PETs were simply considered as students that were learning about NOS in the context of a particular case of HOS. However, educational experiences such as this might also encourage PETs to take an interest in NOS, and therefore to award it a comparable status to more conventional content of the school science curriculum. In addition, it can be useful for PETs to get to know an educational resource with which to address NOS aspects in their own science classes. Nevertheless, all these issues should be analysed in depth in next studies.

Acknowledgments

The author would like to thank his colleague and friend José Antonio Acevedo-Díaz for his collaboration in the analysis of the data in this study.

Funding Information

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

REFERENCES

Abd-El-Khalick, F. (2012). Nature of science in science education: Toward a coherent framework for synergistic research and development. In B. J. Fraser, K. Tobin, & C. J. McRobbie (eds.), *Second International Handbook of Science Education* (pp. 1041-1060). Dordrecht: Springer.

Abd-El-Khalick, F., & Lederman, N. G. (2000). The influence of history of science course on students' views of nature of science. *Journal of Research in Science Teaching*, *37*(10), 1057-1095.

Acevedo, J. A. & García-Carmona, A. (2016a). «Algo antiguo, algo nuevo, algo prestado». Tendencias sobre la naturaleza de la ciencia en la educación científica [«Something old, something new, something borrowed». Trends on the nature of science in science education]. *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias, 13*(1), 3–19.

Acevedo, J. A., & García-Carmona, A. (2016b). Rosalind Franklin y la estructura del ADN: un caso de historia de la ciencia para aprender sobre la naturaleza de la ciencia [Rosalind Franklin and the DNA molecular structure: A case of history of science to learn about the nature of science]. *Revista Científica, 25*, 162–175.

Acevedo-Díaz, J. A. & García-Carmona,A. (2017). *Controversias en la historia de la ciencia y cultura científica [Controversies in history of science and scientific culture]*. Madrid: Los Libros de la Catarata.

Acevedo-Díaz, J. A., García-Carmona, A. & Aragón, M. M. (2017). *Enseñar y aprender sobre naturaleza de la ciencia mediante el análisis de controversias de historia de la ciencia. Resultados y conclusiones de un proyecto de investigación didáctica [Teaching and learning about the nature of science through the analysis of controversies of history of science. Results and conclusions of a didactic research project]*. Madrid: OEI.

Adúriz-Bravo, A., & Izquierdo, M. (2009). A research-informed instructional unit to teach the nature of science to pre-service science teachers. *Science & Education, 18*(9), 1177-1192.

Akerson, V. L., & Donnelly, L. A. (2010). Teaching nature of science to K-2 students: What understandings can they attain? *International Journal of Science Education, 32*(1), 97-124.

Akerson, V. L., Buck, G. A., Donnelly, L. A., Nargund-Joshi, V., & Weiland, I. S. (2011). The importance of teaching and learning nature of science in the early childhood years. *Journal of Science Education and Technology*, *20*(5), 537-549.

Akerson, V. L., Morrison, J. A., & McDuffie, A. R. (2006). One course is not enough: Preservice elementary teachers' retention of improved views of nature of science. *Journal of Research in Science Teaching*, *43*(2), 194-213.

Allchin, D. (2003). Scientific myth-conceptions. *Science Education, 87*(3), 329-351.

Allchin, D. (2004). Pseudohistory and pseudoscience. *Science & Education, 13*(3), 179-195.

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education, 95*(3), 518-542.

Appleton, K. (2008). Developing science pedagogical content knowledge through mentoring elementary teachers. *Journal of Science Teacher Education, 19*(6), 523-545.

Aragón, M.M., García-Carmona, A., & Acevedo, J. A. (2016). Aprendizaje de estudiantes de secundaria sobre la naturaleza de la ciencia mediante el caso histórico de Semmelweis y la fiebre puerperal [Secondary students' learning about the nature of science through the historical case of Semmelweis and childbed fever]. *Revista Científica, 27*, 302–317.

Aragón, M. M., Acevedo, J. A., & García-Carmona, A. (2019). Prospective biology teachers' understanding of the nature of science through an analysis of the historical case of Semmelweis and childbed fever. *Cultural Studies of Science Education, 14*(3), 525-555.

Armstrong, D., Gosling, A., Weinman, J., & Marteau, T. (1997). The place of inter-rater reliability in qualitative research: an empirical study. *Sociology*, *31*(3), 597-606.

Bell, R. L., Mulvey, B. K. & Maeng, J. L. (2012). Beyond understanding: Process skills as a context for nature of science instruction. In M. S. Khine (ed.), *Advances in Nature of Science Research* (pp. 225-245). Dordrecht: Springer.

Bilican, K. & Cakıroglu, J. (2011). A case study on pre-service science teachers' self-efficacy beliefs on teaching nature of science. Paper presented at the *European Educational Research Association Conference 2011.* Freie Universität Berlin.

Bonil, J. & Márquez, C. (2011). ¿Qué experiencias manifiestan los futuros maestros sobre las clases de ciencias? Implicaciones para su formación [What science class experiences do future teachers report? Implications for science teacher education]. *Revista de Educación, 354*, 447-472.

Bybee, R. W. (1997). *Achieving scientific literacy: from purposes to practices*. Portsmouth, NH: Heinemann.

Capps, D. K. & Crawford, B. A. (2013). Inquiry-based professional development: What does it take to support teachers in learning about inquiry and nature of science? *International Journal of Science Education, 35*(12), 1947-1978.

Clough, M. P. (2011). Teaching and assessing the nature of science. *The Science Teacher, 78*(6), 56-60.

Clough, M. P. (2018). Teaching and Learning About the Nature of Science. *Science & Education, 27*(1-2), 1-5.

Dagher, Z. R. & Erduran, S. (2016). Reconceptualizing the nature of science for science education. Why does it matter? *Science & Education*, *25*(1-2), 147-164.

Driver, R., Leach, J., Millar, R. & Scott, P. (1996). *Young People's Images of Science*. Buckingham, UK: Open University Press.

Elliot, J. (2000, 4th ed.). *La investigación-acción en educación* [*Action research in education*]. Madrid: Morata.

García-Carmona, A., & Acevedo, J. A. (2016). Concepciones de estudiantes de profesorado de Educación Primaria sobre la naturaleza de la ciencia: Una evaluación diagnóstica a partir de reflexiones en equipo [Preservice primary teachers' conceptions on the nature of science: A diagnostic assessment from reflections made in small work teams]. *Revista Mexicana de Investigación Educativa, 21*(69), 583–610.

García-Carmona, A., & Acevedo-Díaz, J. A. (2017). Understanding the nature of science through a critical and reflective analysis of the controversy between Pasteur and Liebig on fermentation. *Science & Education, 26*(1-2), 65–91.

García-Carmona, A., & Cruz-Guzmán, M. (2016). ¿Con qué vivencias, potencialidades y predisposiciones inician los futuros docentes de Educación Primaria su formación en la enseñanza de la ciencia? [What personal experiences, potentialities and predispositions do prospective primary teachers manifest when they start their training in science teaching?] *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias, 13*(2), 440–458.

García-Carmona, A., Cruz-Guzmán, M. & Criado, A. M. (2014) '¿Qué hacías para aprobar los exámenes de ciencias, qué aprendiste y qué cambiarías?'. Preguntamos a futuros docentes de Educación Primaria [Scientific literacy at the 3-6 year old stage: an analysis of Spain's national curriculum]. *Investigación en la Escuela, 84*, 31–46.

Gogolin S, & Krüger, D. (2018). Students' understanding of the nature and purpose of models. *Journal of Research in Science Teaching*, *55*(9), 1313-1338.

Guisasola, J., & Morentin, M. (2007). ¿Comprenden la naturaleza de la ciencia los futuros maestros y maestras de educación primaria? [Do pre-service primary teachers understand the nature of science?] *Revista Electrónica de Enseñanza de las Ciencias, 6*(2), 246-262.

Hanuscin, D. L., Lee, M. H., & Akerson, V. L. (2011). Elementary teachers' pedagogical content knowledge for teaching the nature of science. *Science Education*, *95*(1), 145-167.

Hodson, D. (2014). Nature of Science in the Science Curriculum: Origin, Development, Implications and Shifting Emphases. In M. R. Matthews (ed.), *International Handbook of Research in History, Philosophy and Science Teaching* (pp. 911-970). Dordrecht: Springer.

Irwin, A. R. (2000). Historical case studies: Teaching the nature of science in context. *Science Education, 84*(1), 5-26.

Irzik, G., & Nola, R. (2014). New directions for nature of science research. In M. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 999-1021). Dordrecht: Springer.

Justi, R., & Mendonça, P. C. C. (2016). Discussion of the controversy concerning a historical event among pre-service teachers. Contributions to their knowledge about science, their argumentative skills, and reflections about their future teaching practices. *Science & Education, 25*(7-8), 795–822.

Kampourakis, K. (2016). The "general aspects" conceptualization as a pragmatic and effective means to introducing students to nature of science. *Journal of Research in Science Teaching*, *53*(5), 667-682.

Khishfe, R., & Lederman, N. (2007). Relationship between instructional context and views of nature of science. *International Journal of Science Education*, *29*(8), 939-961.

Laherto, A. M. P., Kampschulte, L., de Vocht, M., Blonder, R., Akaygün, S., & Apotheker, J. (2018). Contextualizing the EU's "Responsible Research and Innovation" policy in science education. *Eurasia Journal of Mathematics, Science & Technology Education*, *14*(6), 2287-2300.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (eds.), *Handbook of Research on Science Education* (pp. 831-879). Mahwah, NJ: Lawrence Erlbaum.

Lederman, N. G., & Abd-El-Khalick, F. (1998). Avoiding de-natured science: Activities that promote understandings of the nature of science. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 83-126). Dordrecht: Kluwer Academic.

Lin, J. W. (2014). Elementary school teachers' knowledge of model functions and modeling processes: a comparison of science and non-science majors. *International Journal of Science and Mathematics Education*, *12*(5), 1197-1220.

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Beverly Hills, CA: Sage.

Martín del Pozo, R., Fernández-Lozano, P., González-Ballesteros, M., & de Juanas, Á. (2013). El dominio de los contenidos escolares: competencia profesional y formación inicial de maestros [Mastery of content: Professional competences and pre-service teacher education]. *Revista de Educación*, *360*, 363-387.

Martins, A. F. P. (2015). Natureza da Ciência no ensino de ciências: Uma proposta baseada em "temas" e "questões" [The nature of Science in Science teaching: a proposal based on "issues" and "questions"]. *Caderno Brasileiro de Ensino de Física*, *32*(3), 703-737.

Matthews, M. R. (2012). Changing the focus: From nature of science (NOS) to features of science (FOS). En M. S. Khine (ed.), *Advances in Nature of Science Research* (pp. 3-26). Dordrecht: Springer.

Matthews, M. R. (2015). Science teaching: The contribution of history and philosophy of science (20th Anniversary Revised and Expanded ed.). New York, NY: Routledge.

Mayring, Ph. (2000). Qualitative Content Analysis. *Forum: Qualitative Social Research, 1*(2), 1-10.

McComas, W. F. (2004). Keys to teaching the nature of science. *The Science Teacher*, *71*(9), 24-27.

McComas, W. F. (2008). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education, 17*(2-3), 249-263.

Michel, H., & Neumann, I. (2016). Nature of science and science content learning. *Science & Education*, *25*(9-10), 951-975.

Monk, M., & Osborne, J. (1997). Placing the history and philosophy of science on the curriculum: A model for the development of pedagogy. *Science Education, 81*(4), 405-424.

Newman, W. J., Abell, S. K., Hubbard, P. D., McDonald, J., Otaala, J., & Martini, M. (2004) Dilemmas of teaching inquiry in elementary science methods. *Journal of Science Teacher Education, 15*(4), 257-279.

NGSS Lead States (2013). *The Next Generation Science Standards: For States, by States*. Washington, DC: National Academy of Sciences Press.

Oliva, J. M., & Acevedo, J. A. (2005). La enseñanza de las ciencias en primaria y secundaria hoy. Algunas propuestas de futuro [Science teaching in primary and secondary education today. Some proposals for future]. *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias, 2*(2), 241-250.

Organisation for Economic Co-operation and Development [OECD] (2017). *PISA 2015 Assessment and Analytical Framework: Science, Reading, Mathematic, Financial Literacy and Collaborative Solving Probem*. Paris: OECD Publishing.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching*, *40*(7), 692-720.

Rudge, D. W., & Howe, E. M. (2009). An explicit and reflective approach to the use of History to promote understanding of the nature of Science. *Science & Education, 18*(5), 561-580.

Rudge, D. W., Cassidy, D. P., Fulford, J. M., & Howe, E. M. (2014). Changes observed in views of nature of science during a historically based unit. *Science & Education, 23*(9), 1879-1909.

Salmerón, L. (2013). Actividades que promueven la transferencia de los aprendizajes: una revisión de la literatura [Activities that promote transfer of learning: a review of the literature]. *Revista de Educación*, *No. Extraordinario*, 34-53.

Seale, C. (1999). *The quality of qualitative research. Introducing qualitative methods series*. London: SAGE.

Shamos, M. H. (1995). *The myth of scientific literacy.* New Brunswick, NJ: Rutgers University Press.

Shenton, A. K. (2004). Strategies for ensuring trustworthiness in qualitative research projects. *Education for Information*, *22*(2), 63-75.

Sohr, E. R., Gupta, A., & Elby, A. (2018). Taking an escape hatch: Managing tension in group discourse. *Science Education*, *102*(5), 883-916.

Treagust, D. F., Chittleborough, G., & Mamiala,T. L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education*, *24*(4), 357-368.

Verdugo, J. J., Solaz-Portolés, J. J., & Sanjosé, V. (2016). Pre-service primary school teachers' science content knowledge: An instrument for its assessment. *International Journal of Innovation in Science and Mathematics Education*, *24*(2), 37-51.

Wallace, J. (2017). Teaching NOS in an age of plurality. *Canadian Journal of Science, Mathematics and Technology Education*, *17*(1), 1-2.

Williams, C. T., & Rudge, D. W. (2016). Emphasizing the history of genetics in an explicit and reflective approach to teaching the nature of science. A pilot study. *Science & Education, 25*(3-4), 407-427.