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# Teaching the Nature of Science Through the Millikan-Ehrenhaft Dispute

**Eleni Paraskevopoulou · Dimitris Koliopoulos**



**Abstract** This article presents the results of a research project that investigated the extent to which the use of the historical episode of the Millikan-Ehrenhaft dispute over the existence of the elementary electric charge can improve students' conceptions of specific aspects of the Nature of Science (NOS). A teaching programme containing seven hourly teaching units was designed and implemented. The teaching intervention was designed on the basis of an explicit form of teaching that was integrated into the scientific content and through the use of short stories. Students' conceptions of specific aspects of NOS were documented in a questionnaire distributed before and after the class. The results showed that there was a significant statistical improvement in students' conceptions of the aspects of NOS that had been selected for teaching.

## 1 Introduction

Many scholars have supported the use of the history of the natural sciences as a framework for teaching aspects of Nature of Science (NOS) (Irwin 2000; Klopfer 1969; Matthews 1994; Monk and Osborne 1997). In 1969 Khoper stated that the history of science has the potential to provide an insight into the procedural, contextual and conceptual aspects of science. Rudge and Howe (2004) have proposed a framework for the teaching of history of science in biology classes in primary and secondary education. They argue that the main advantage of planning lessons in which aspects of the history of the natural sciences have been incorporated is that this gives students the ability to approach important concepts in biology as well as issues relating to NOS. Several scholars (Clough 2003; Ryder et al. 1999) have also argued that the explicit teaching of NOS as 'incorporated' within the

E. Paraskevopoulou (✉)
Geitonas Schools, 16672 Athens, Greece
e-mail: eparask62@gmail.com

D. Koliopoulos
University of Patras, Patras, Greece
e-mail: dkoliop@upatras.gr

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natural sciences curriculum could also lead to an improvement in students' conceptions of NOS. Clough (2003) has argued that when NOS activities are not connected to the scientific content it will not be possible for students to develop sufficient conceptions of NOS.

On the other hand, Abd-El-Khalick and Lederman (2000) have shown that in order for NOS teaching to be effective there must be a specific reference to NOS aspects that can be presented through a historical example or through the teaching of a scientific subject. In other words, the research showed that students are not able to understand NOS aspects simply through the presentation of a historical example or by engaging in scientific activities when there is no explicit reference to the NOS aspects that they present. Niaz (2000), Kolstø (2008) and McComas (2008) have also argued that the history of the natural sciences and specifically the Millikan-Ehrenhaft dispute over the electron can be used in the teaching and full understanding of NOS aspects.

The object of the study presented in this article was to investigate if incorporating the Millikan-Ehrenhaft dispute into teaching can contribute to the construction of specific aspects of NOS on the part of the students. For this purpose a teaching intervention was planned and implemented in the context of which explicit reference was made to those aspects of NOS that are to be taught. The teaching of these NOS aspects is incorporated into the scientific content which is to be taught and brief stories are related, the object of which is to present the specific NOS aspects in combination with the scientific content.

## 2 Theoretical Framework

### 2.1 The Scientific Dispute as a Tool for Introducing NOS Aspects into Teaching

NOS can generally be defined as '…a hybrid domain which blends aspects of various social studies of science including the history, sociology and philosophy of science combined with research from the cognitive sciences such as psychology into a rich description of science; how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors' (McComas et al. 1998, p. 4). One of the most interesting and productive recent discussions of studies on NOS has focused on defining key NOS ideas, which are deemed suitable for incorporation into the natural sciences curriculum in primary and secondary education.

Some key ideas include the understanding that scientific knowledge demands and is based upon empirical evidence, is tentative (subject to change), is partially a product of the human imagination and creativity, has a subjective character (is influenced by the scientist's previous knowledge, his or her experiences and prejudices), and is socially and culturally influenced (McComas 2004). Another interesting key idea is the distinction between observations and inferences, as discussed by Khishfe and Lederman (2006).

Having established the key ideas in the teaching of NOS, the efforts of science education researchers has turned to the question of how these ideas can be made an object of learning for both students and future educators. McComas (2008), after a study of NOS books for the general public, came to the conclusion that the use of historical examples and vignettes provides a frame through which it is possible to teach students the key NOS ideas discussed above. In this study, McComas linked specific historical examples with specific key NOS ideas. Clough and Olson (2004) argue that just as educators often use practical activities as evidence to convince students of scientific concepts, historical and contemporary episodes in science could similarly be used as evidence to convince students of specific key NOS ideas.

Inherent to the natural sciences are issues which often involve conflict or dispute between ‘experts’. One such example is the dispute over and the extent to which electromagnetic radiation from power lines can be related to an increased risk of childhood leukaemia (Ahlbom and Feycting 2003). Kipnis (2001) argues that to demonstrate in the classroom that scientific knowledge is an issue that can be debated can contribute to making science similar to other human activities which are easier to comprehend, such as a political debate, and can also spark an interest for science in some students. In his paper Kipnis uses the examples of the controversies over ‘animal’ electricity and ‘contact’ electricity that took place between Volta and Galvani, as well as the controversy over the nature of battery electricity between Volta and, this time, the British chemist Sir Humphrey Davy. More recently, Izquierdo et al. (2006) have used the dispute between Pouchet and Pasteur over spontaneous generation as a way of enabling students specialising in Natural Sciences and Philosophy to understand scientific activity and the processes by which knowledge is produced through experiments, dialogue and social consensus.

As has already been stated, the dispute between Millikan and Ehrenhaft over the existence or otherwise of the elementary charge can be used to introduce natural science aspects of NOS into the classroom and, in particular, to demonstrate the subjective character of scientific knowledge (McComas 2008). In a recent study, Klassen (2009) introduced aspects of Millikan’s oil-drop experiment when teaching the experiment to second-year university students, in an attempt to overcome the problems the students had in collecting data with satisfactory precision and in the interpretation of data. Klassen puts particular emphasis on Millikan’s relationship with his postgraduate student Harvey Fletcher, who played an important role in the effective execution of the experiment. This is done in order to humanise the two protagonists so as to stimulate the interest of the students. Moreover, the students are brought into contact with further historical material prior to the experiment, which enables them to think upon the fundamental nature of electricity.

The present study is, as far as we are aware, one of the few studies in which an attempt is made to explore aspects of the didactic transposition of the historic dispute between Millikan and Ehrenhaft in secondary education and to present the findings related to the type of teaching intervention and the characteristics of students’ cognitive development of NOS subjects.

### 2.2 The Historical Episode of the Millikan-Ehrenhaft Dispute

The historical episode used in the proposed teaching intervention is the dispute between Millikan and Ehrenhaft over the existence of the elementary electrical charge, often referred to as the ‘battle over the electron’. The episode took place around 1910 and led the two protagonists in diametrically opposed directions: one to success and a Nobel Prize, the other to failure and obscurity. Millikan believed in the hypothesis that there was an elementary electric charge, that of the electron. He put forward the atomic theory of electricity: the approach, that is, that there was in nature an elementary electric charge of which all bodies consisted. Ehrenhaft, on the other hand, believed that there was no universal charged particle, and that there were small particles whose charge was a fraction of the charge of the electron. He adopted the explanation of continuity for electricity. Ehrenhaft was influenced by the philosophical trend favouring the continuity of the structure of matter which flourished in continental Europe, and whose chief exponent was Mach.

Millikan and Begeman (1908) initially used the Wilson method, which was based on the study of a cloud of vapour droplets that moved under the influence of a gravity and electric field. Using this method, Millikan and his student Louis Begeman found a mean value for the elementary electric charge which was somewhat smaller than that expected, and with a wide range of values. This wide range could have led to the conclusion that the charge can take on any value, and that there are no integral multiples of the minimum electric charge. Millikan himself notes that: "*Indeed the instability, distortion and indefiniteness of the top surface of the cloud were somewhat disappointing, and the results were not considered worth publishing*" (Millikan 1947, pp. 55–57).

This experimental result, instead of leading Millikan to the conclusion that his hypothesis on the quantisation of the charge was mistaken, led him instead to the need to improve the experimental method he was using. After constant improvements to his experimental method, Millikan succeeded in calculating a value for the elementary electric charge very close to that expected, and in 1910 he embarked on the first important publication of his results. In this, Millikan explained the way in which he assessed his measurements. "*The observations marked with a triple star are those which were marked 'best' in my notebook … The double starred observations were marked in my notebook 'very good'. Those marked with single stars were marked 'good' and the others 'fair'*" (Millikan 1910, p. 220).

The controversy started when in this article Millikan criticised the accuracy of the results which Ehrenhaft had published, in spite of the fact that the results and the method which he used resembled his own. Ehrenhaft responded to Millikan's criticism in a subsequent article in which he calculated the charge of each droplet for each of Millikan's observations separately. The result was a very wide range of values for the droplet's charge, not all of them an integral multiple of the elementary one. This result weakened the argument for the existence of the universal electric charge. Ehrenhaft's view was that Millikan's conviction as to the existence of the elementary electric charge had led him to show a high level of error in the values. Millikan's view of the way in which Ehrenhaft handled the data was that it "would force one to turn one's back on a basic fact of nature—the integral character of *e* [the charge of the electron]" (Holton 1978, p. 69).

A new dimension was added to the Millikan-Ehrenhaft dispute when Gerald Holton discovered two of Millikan's laboratory notebooks in the archives of the California Institute of Technology. These notes (28 October 1911–16 April 1912, approximately 175 pages) provide a rare opportunity to see the work of a scientist in his laboratory. The notes had raw data, and from these some of the data selection processes which were used in the article published in the *Physical Review* (Millikan 1913) can be seen. On the other hand, Ehrenhaft's notes were lost in the Second World War, when he emigrated to the United States after Austria had been taken over by the Nazis. In Millikan's laboratory notes there were measurements for 140 droplets, whereas the published results in 1913 state emphatically that there were measurements for 58 droplets. What happened to the other 82? Millikan did not use the values of the electron charge which were contrary to his initial idea, and it seems that the reason that he did not take into account more than half the data was the guiding hypotheses which he held.

As can be seen from the above, the nature of the Millikan-Ehrenhaft dispute provides an excellent context for teaching key NOS ideas related to:

– *the role played by empirical data in scientific debate*. In the 'battle over the electron' the entire debate between the two protagonists and the scientific debate was conducted on the basis of the empirical data collected during their corresponding experiments.

The existence of empirical data is essential for the debate to begin on how accurate they may or may not be, how they may be improved, how are they critically evaluated and how, ultimately, is it possible to interpret them. Throughout the whole process both Millikan and Ehrenhaft attempted to improve their experimental methods, removing possible sources of error so as to produce more precise results.

– *the distinction between observation and inference*. As Khishfe and Lederman (2006) write, "observations are descriptions of nature that can be directly accessed by the senses, whereas inferences cannot be directly accessed by the senses. For example, scientists make observations about the change in the climate and then they use these observations to infer about the possible reasons behind the global warming" (p. 400). The Millikan-Ehrenhaft dispute offers a number of opportunities for discussing this issue. Such opportunities include the relationship between Millikan's neglected observations with the conclusions of his inference, or the fact that two scientists might come up with two different inferences when discussing the same observations (in our case the row data form Millikan's notebook—Holton 1978).
– *the role of the scientist's imagination and creativity in the formation of theory in the natural sciences*. The role played by imagination and creativity is apparent in the fact that Millikan continuously improved his experimental methods when he could see "an individual electron riding on a drop of oil" and in identifying the possible sources of error that prevailed over the results of an experiment.
– *the fact that the natural sciences have a subjective content during the formation of a theory*. The two scientists used more or less the same experimental arrangement and collected similar experimental data, yet their different guiding hypotheses meant that they interpreted them completely differently. The 'battle over the electron' demonstrates that the idea that the charge is quantised does not derive from the empirical data itself but from its interpretation, which is based on the subjective hypothetical knowledge adopted by each researcher. Of course, this element of NOS if presented in the classroom one-sidedly could lead to relativist epistemological concepts, which are not part of the aims of the proposed teaching intervention.

## 3 Research Methodology

### 3.1 Research Strategy

This is a pre-experimental design, as outlined by Cohen and Manion (1994), whereby a group of students was measured on the basis of a dependent variable (the group's conceptions of certain aspects of NOS) after a sequence of experimental teaching units designed to improve the students' conceptions of NOS had been given. The sequence of experimental teaching units constitutes the independent variable. When the teaching intervention had been completed the group was again measured on the basis of conceptions of NOS. The differences in the team's grading of conceptions of NOS both before and after the teaching intervention were then studied, the differences being attributed to the effect of the specific sequence of experimental teaching units that was used. In order to interpret the difference between the grades as regards the team's conceptions of NOS before and after the intervention, hypotheses were formulated based on a study of the students' responses and the worksheets that they had completed during the teaching intervention.

### 3.2 The Sample

A total number of twenty-four (24) students took part in the study, four boys and twenty girls. They were students of the second grade of high school (ages 16–17) who were taking a physics class specifically for students who had not chosen classes on the natural sciences for their future professional employment. Prior to the teaching intervention the students had not been taught aspects of NOS incorporated within the scientific content.

## 4 The Teaching Intervention

### 4.1 Characteristics and Content of the Teaching Units

The main guiding principles of the proposed teaching intervention were as follows:

– *the explicit teaching of aspects of NOS as a process incorporated into the natural sciences curriculum of a specific school grade*. This principle is supported by various scholars, such as Abd-El-Khalick and Lederman (2000) and Khishfe and Abd-El-Khalick (2002). The aspects of NOS that it was considered possible to teach were those referred to earlier in the discussion on the nature and character of the Millikan-Ehrenhaft dispute: (a) the role played by empirical data in scientific debate (abbreviated to 'empirical character of the natural sciences'); (b) the 'distinction between observation and inference'; (c) the role of the scientist's imagination and creativity in the formation of theory in the natural sciences (abbreviated to 'imagination and creativity'); and, (d) the fact that the natural sciences have a subjective content during the formation of a theory, in the sense that that scientific construction is influenced by the background knowledge, both scientific and philosophical, of scientists (abbreviated to 'subjectivity in the natural sciences'). A fifth aspect of NOS was also taught, namely the tentativeness of knowledge in the natural sciences. Although, this is not directly derived from the historical example of the Millikan-Ehrenhaft dispute it was considered necessary to incorporate it in order to reinforce the first four aspects. No reference shall be made to the results pertaining to this aspect.
– *the creation of short stories through which the specific dispute over the quantisation of the electric charge was presented*. The so-called story-line approach is a '*local*' approach of the curriculum according to which the teacher may use functional texts from the history of science as opportunities for reading and contemplation as well as for comparison or correlation. The aim here is for "the students to compare their progress in relation to the epistemological obstacles overcome by scientists in the past" (Martinand 1993, p. 96). The important point in the story-line approach is that the historical material is followed by teaching situations based on the introduction and solving of problems which should interest students (Roach 1993; Clough and Olson 2004; Koliopoulos et al. 2007).

One of the advantages of the creation and introduction of texts from the history of science, within the framework of the story-line approach and their 'localised' use, is the acceptance by teachers who may use short and functional material (Monk and Osborne 1997) and, in addition, are not obliged to form complete perceptions of the history and philosophy of science. Four short stories were devised, the aim of which was to highlight the specific scientific content and to help the students gain a better understanding of the aspects of NOS which had been chosen to be taught. At the end of each short story there was a question, the aim of which was to focus the students' attention on the specific aspect of NOS which was highlighted in the short story.

The aim of the first story was to draw attention to the fact that the natural sciences seek, produce, and are based upon empirical data. Thus this story deals with all the attempts to measure the elementary unit of the electric charge, from Townsend (1897) to the first results of Millikan's measurements in 1910. The second short story aimed to highlight the distinction between 'observation' and 'inference'. This story includes an extract from Millikan's autobiography in which a distinction was made between those items which are a product of observation during the experimental process and those which are a product of the thought and inference of the scientist. The third story highlights the subjective character of scientific knowledge. More specifically, it deals with the differing interpretation given by Millikan and Ehrenhaft to the similar experimental data which they had collected. Finally, the fourth short story demonstrates that although scientific knowledge may be subjective in nature as it is being constructed, this subjectivity is limited by the fact that it is the scientific community that will accept or reject this scientific view.

– *the adoption of a modified form of the teaching model proposed by Monk and Osborne* (1997). These scholars suggest a teaching model for the incorporation of the history of science in science teaching, where the dominant element is the comparison of ideas deriving from the history of science, students' ideas and contemporary ideas on a thematic scientific field and aspects of NOS.

### 4.2 Teaching the Unit

The purpose of the proposed teaching intervention was to transpose the basic ideas of the relationship between the historical episode of the Millikan-Ehrenhaft dispute and the highlighting of NOS aspects in a sequence of teaching units. The proposed teaching intervention is comprised of seven units, of which the first and the seventh were used to evaluate the teaching intervention. In the remaining teaching units the students were given worksheets containing the short stories outlined above accompanied by questions which acted as starting points for discussing the various aspects of NOS that were to be taught. More specifically, in the second teaching unit the students were presented with the historical and cultural context in which the question of the quantisation or otherwise of the electrical charge arose. There was also mention and discussion of the two guiding theses of quantisation and the continuity of the electrical charge, as expressed by Millikan and Ehrenhaft respectively. In the third teaching unit there was a presentation of Millikan's oil drop experiment after which the students were given worksheets containing hypothetical data from the experiment and questions that sought to engage them in a discussion of the various interpretations that could be given for this data. In the fourth, fifth and sixth teaching units the short stories on the Millikan-Ehrenhaft dispute were introduced, each one accompanied by questions intended to focus the children's attention on a different aspect of NOS. Appendix 1 contains the third short story as a typical example of a worksheet, along with the questions that provided the focus of the discussion between the teacher and the students of the NOS aspect 'distinction between observation and inference'.

## 5 The Questionnaire and Analysis of the Results

A questionnaire (see Appendix 2) was used before and after the teaching intervention in order to explore the conceptions of students towards the aspects of NOS that had been selected for this particular study. The questions used were based on a modified version of another questionnaire, as used by Khishfe and Lederman (2006) in a similar study. Each question corresponds to the investigation of one or more aspects of NOS (see Appendix 3), so as to be able to investigate each NOS aspect within a different context of treatment. For example, the 'imagination and creativity' aspect is investigated in the second, third and fourth questions of the questionnaire.

The students' responses to each question were categorised as exhibiting '*naive*', '*informed*' and '*transitional*' conceptions. This categorisation is the same as that used by Khishfe and Lederman (2006) in their own study mentioned above. In order for a student's view towards a particular aspect of NOS to be categorised as 'informed', he or she would have to be categorised as having an 'informed' view in all the contexts. A view was characterised as 'naive' if the student exhibited a naive view in all four contexts. Finally, if a student exhibited 'informed' conceptions in some contexts but not all of them, their view was categorised as 'transitional'. For example, the conceptions of students who exhibited 'informed' conceptions as regards the 'tentative' aspect in one, two or three contexts were categorised as 'transitional'. The categorisation of the students' views for the remaining aspects of NOS was done in the same way.

## 6 Research Results

### 6.1 Empirical Character of the Natural Sciences

Figure 1 shows the results of the student's views from questions relating to the empirical character of scientific knowledge both before and after the teaching intervention.

Students' conceptions of this aspect of NOS were based on responses to the first, second and third questions in the questionnaire. The non-parametrical test for two related samples, specifically the Wilcoxon test, demonstrated a significant statistical change in the students' conceptions as regards the empirical character of scientific knowledge after the teaching intervention ($N = 24$, $z = -3.50$, $p = 0.000 < 0.05$). The results showed, that is, that the variable that correlates with the 'empirical character of the natural sciences after the

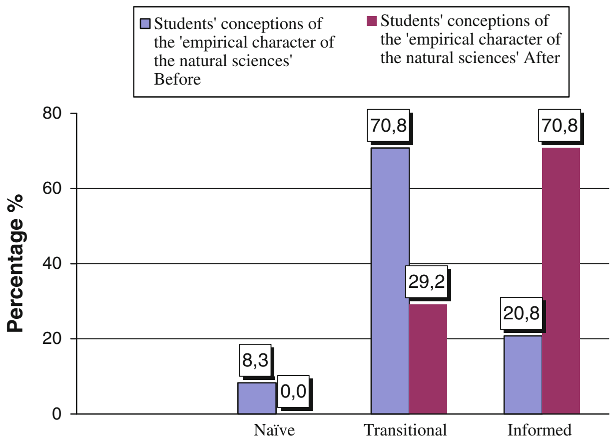



**Fig. 1** Students' conceptions of the 'empirical character of the natural sciences' before and after the teaching intervention

teaching intervention' tends to have values that are greater than or equal to the variable that correlates to the 'empirical character of the natural sciences before the teaching intervention' and in no case does it have a lower value. More specifically, after the teaching intervention 13 students tended to improve their understanding of the empirical character of scientific knowledge, 11 students did not change their conceptions and no student appeared to have worse conceptions than those they had prior to the teaching intervention.

There now follows a characteristic example of a 'transitional' conception that was exhibited by one female student before the teaching intervention. Female student M-20 appears not to understand the role of empirical data in the validation of or change to a theory:

> I believe that it's pretty difficult for theories, the laws to change because these laws and theories have been proved for so many years and so much has been supported on the basis of them. [M20, Question 1]

Even so, this student appears to understand that the representation of the form of an atom is based on empirical data:

> Scientists have determined the form of the atom after many studies of the movements and observations of the atom under a microscope. [M20, Question 2]

Moreover, the same student appears to understand the role of empirical data in the representation of the appearance of dinosaurs:

> Scientists use the bones and other finds that were discovered, as well as the study of DNA to imagine the appearance of dinosaurs. [M20, Question 3]

The change in the students' conceptions of the 'empirical character of the natural sciences' after the teaching intervention can be seen in the extracts below from the responses of another female student, who exhibited 'informed' conceptions to the three questions.

> Yes, scientific knowledge can change because with the development of technology something new, different can be discovered, which can lead to the change of some theories. [M23, Question 1]
> Scientists, through experiments and observations have come to conclusions as to what the structure of an atom may be like, as they have not been able to see it under a microscope. [M23, Question 2]
> They were able to determine the appearance of dinosaurs by combining finds (bones, fossils) with specialised knowledge of the anatomy of lizards, which are direct ancestors of the dinosaurs. They could thus make inferences about the appearance of various types of dinosaur. [M23, Question 3]

### 6.2 The Distinction Between Observation and Inference

Figure 2 shows the results of the student's views from questions relating to the 'distinction between observation and inference' both before and after the teaching intervention.

Students' conceptions of this aspect of NOS were based on responses to the second and third questions in the questionnaire.

The Wilcoxon test showed that there is a significant statistical change in the students' conceptions after the teaching intervention ($N = 24$, $z = -2.530$, $p = 0.011 < 0.05$). The results showed, that is, that the variable that correlates with the 'distinction between

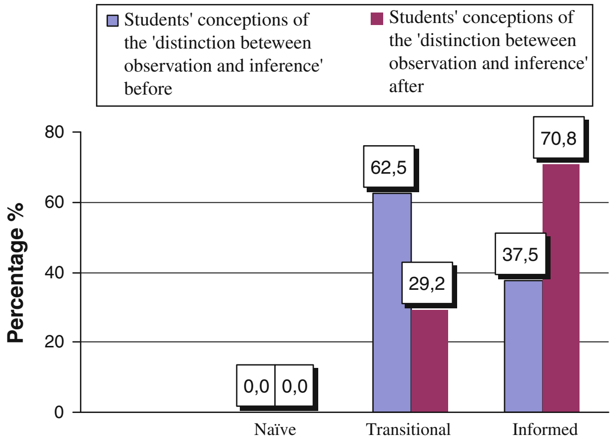



**Fig. 2** Students' conceptions of the 'distinction between observation and inference' before and after the teaching intervention

observation and inference after the teaching intervention' tends to have values that are greater than or equal to the variable that correlates to the 'distinction between observation and inference prior to the teaching intervention' and in only one case did it have a lower value. More specifically, after the teaching intervention 9 students tended to improve their conceptions, 14 students did not change their conceptions and one student appeared to have worse conceptions than before the teaching intervention, always in relation to this specific aspect of NOS.

The example which follows gives the response of female student M13, who appears not to have understood the distinction between what is a product of observation and what a product of inference in the case of the structure of the atom:

> Scientists have seen the atom through a microscope. Since they had seen it through a microscope it was very simple to adapt it to a computer programme. [M13, Question 2]

Despite this, the same student appears to understand that the appearance of dinosaurs is the result of inference from empirical data:

> Scientists know of the existence of dinosaurs through their fossils and skeletons, which have been discovered. By studying the fossils and the skeletons they were able to determine the appearance of dinosaurs. Through the use of technology they have been able to create various simulations and to compare them with their finds. [M13, Question 3]

The change in the students' conceptions of the distinction between observation and inference after the teaching intervention can be seen in the following extracts from the responses of another female student, who exhibited 'informed' conceptions to the two questions.

> Scientists have inferred the structure of the atom through hypotheses, observations and experiments over many years. [M1, Question 2]

> Scientists have determined the appearance of dinosaurs through the skeletons that have been found. It is from them that they attempted to imagine how a dinosaur would look. [M1, Question 3]

Another example of ‘informed’ conceptions to both questions after the teaching intervention:

> Through specific experiments, naturally from which, as we said, they did not observe the complete structure of the atom but through specific results, they made certain inferences. [M5, Question 2]
> Through their bones and the fossils that have been found. [M5, Question 3]

### 6.3 Imagination and Creativity

Figure 3 shows the results of the student’s views from questions relating to the aspect of ‘imagination and creativity’ both before and after the teaching intervention.

Students’ conceptions of this aspect of NOS were based on responses to the second, third and fourth questions in the questionnaire.

The Wilcoxon test demonstrated a significant statistical change in the students’ conceptions of the role of imagination and creativity in the natural sciences after the teaching intervention ($N = 24$, $z = -2.324$, $p = 0.020 < 0.05$). The results showed that the variable ‘imagination and fantasy after the teaching intervention’ tends to have values greater or equal to the variable ‘imagination and fantasy before the teaching intervention’, whereas in only one case does it have a smaller value. More specifically, after the teaching intervention 11 students tended to improve their conception, 12 students did not change their conceptions and 1 student appeared to have worse conceptions than before the teaching intervention.

In the following example, female student M23 does not understand the role of imagination and creativity in the production of the structure of the atom:

> Yes, scientists are certain of the structure of the atom, I think that the structure of the atom is a whole and true theory. Scientists have determined the structure of the atom

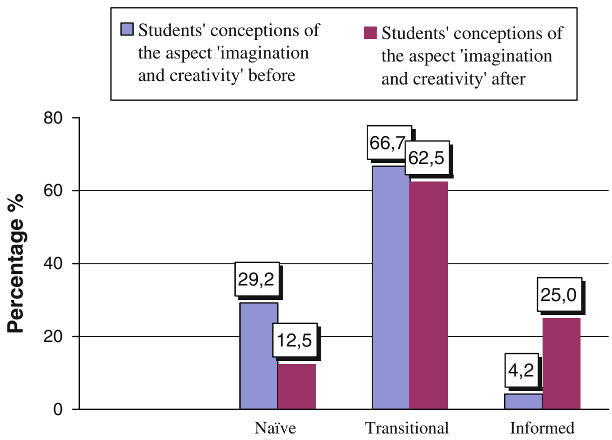



**Fig. 3** Students’ conceptions of the aspect ‘imagination and creativity’ before and after the teaching intervention

> through many experiments and research involving specially-*equipped microscopes.* [M23, Question 2]

Even so, she appears to understand the role of imagination and creativity in the production of the appearance of dinosaurs. Moreover, she also appears to understand that scientists use their imagination and creativity in the interpretation and construction of theories:

> By combining their finds and their knowledge of the physiology of reptiles (which are considered descendants of dinosaurs) they were able to make particularly accurate hypotheses. [M23, Question 3]
> Yes. Imagination is necessary and leads them down different roads where they can find explanations and solutions to their questions. Also, one must have imagination in order to create theories for those things that exist around them, and then they can verify them. [M23, Question 4]

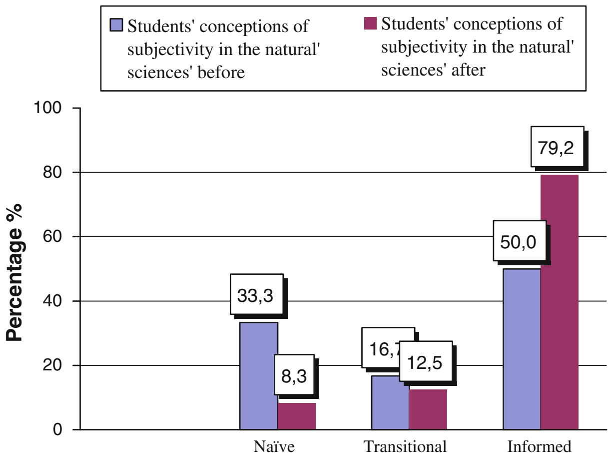
The change in the students' conceptions of the 'imagination and creativity' aspect after the teaching intervention can be seen in the following extracts from the responses of another female student, who exhibited 'informed' conceptions to the three questions.

> I believe that the theory that supports this particular structure emerged as the prevailing one among the scientific community. It obviously also matched the data from some experimental procedures. [M11, Question 2]
> Scientists managed to determine the appearance of dinosaurs through a study of their fossils, their 'related' species that survive today and through the possible causes that led to their extinction. [M11, Question 3]
> Yes, scientists use their imagination since they create guiding hypotheses which they then attempt to validate. [M11, Question 4]

## 6.4 Subjectivity in the Natural Sciences

Figure 4 shows the results of the student's conceptions from questions relating to the aspect of 'subjectivity in the natural sciences'.

**Fig. 4** Students' conceptions of 'subjectivity in the natural sciences' before and after the teaching intervention



Students' conceptions of this aspect of NOS were based on responses to the third and fifth questions in the questionnaire. The Wilcoxon test demonstrated a significant statistical change in the students' conceptions of the role of subjectivity in the natural sciences after the teaching intervention (N = 24, z = −2.739, $p = 0.006 < 0.05$). The results showed that the variable 'subjectivity in the natural sciences after the teaching intervention' tends to have values greater or equal to the variable 'subjectivity in the natural sciences before the teaching intervention', and in no case does it have a smaller value. More specifically, after the teaching intervention 9 students tended to improve their conceptions, 15 students did not change their conceptions and no students appeared to have worse conceptions than before the teaching intervention.

The following examples are typical of the 'naive' conception of this aspect of NOS:

> Scientists may draw different inferences when they all use the same data because each one uses different methods and different experiments to discover it. [M6, Question 3]
> The two scientists, Millikan and Ehrenhaft, were able to draw different inferences because each one used different experiments and based their work on different theories. [M6, Question 5]

The same female student who exhibited 'naive' conceptions before the teaching intervention appeared after the teaching intervention to understand that scientists can draw different inferences even when they have the same data in front of them, because of their different views and prior knowledge and experiences:

> Scientists can draw different inferences when they all use the same data because each one uses the data based on his experience and his own knowledge. In this way it is very likely that they will draw different inferences. [M6, Question 3]
> These two scientists, Millikan and Ehrenhaft, were able to draw different inferences because each one used his own prior knowledge and experiences to draw inferences. [M6, Question 5]

## 7 Discussion and Conclusions

The purpose of this study was to investigate whether the historical episode of the Millikan-Ehrenhaft dispute over the existence of the elementary electric charge can be used as a teaching context in order to improve students' views of the aspects of NOS discussed above. The results of the students' responses to the questions demonstrate that there was an improvement in the views of the students and in their understanding of the five characteristics of scientific knowledge which were investigated through the questionnaire.

More specifically, it can be seen that:

# There was an improvement in the conceptions of many students after the teaching intervention in all four aspects of NOS.
# There was a statistically significant improvement in the students' conceptions for each of the four aspects of NOS.
# Although prior to the teaching intervention no student had exhibited 'informed' conceptions of all four of the NOS aspects under investigation, after the teaching intervention two students exhibited 'informed' conceptions of all four of the NOS aspects. Moreover, none of the remaining students exhibited only 'simple' conceptions.

The results of this study can be commented upon in terms of the following three factors, which comprise the basic characteristics of the proposed teaching intervention: the process of incorporating aspects of NOS into the context of the scientific content that is to be taught; the introduction of scientific disputes as tools for teaching NOS; and, a teaching model based on short stories containing aspects of the natural sciences. As for the first factor, we note that these results correspond to those of other studies, such as the results of Khishfe and Lederman (2006), where the explicit incorporation of NOS aspects into the content to be taught led to an improvement in students' conceptions of these aspects.

The second factor that we believe may have contributed to the successful results of our study is the fact that instruction in aspects of scientific knowledge was connected to a discussion of a scientific dispute. The results of this study support the views of both McComas (2008) and Kolstø (2008) that Millikan's oil drop experiment is suitable for teaching the subjective and constructive aspects of scientific knowledge. The improvement in the views of the students towards the four aspects of scientific knowledge that were investigated through the questionnaire could be attributed to the fact that the specific issues of the dispute presented the complex situations and challenges that Millikan and Ehrenhaft faced when constructing ideas and defining these ideas on the basis of how well they fit with the empirical data. The students were given the opportunity to comprehend that the knowledge of the existence of an elementary electric charge is not an objective fact which cannot be doubted but is precisely a human invention that was subject to a public debate amongst specialists. It appears that the narration of the dispute helped the students to understand science's internal processes, the introduction of a new theory in particular and its relationship with the experiment.

This is what Kipnis (2001) argues, and he also proposes the use of the dispute between 'animal' electricity and 'contact' electricity that took place between Volta and Galvani, as well as the dispute over the nature of battery electricity between Volta and the British chemist Sir Humphrey Davy. Kipnis argues that a good way of countering the myth that some experiments support one theory and dispute another is precisely to show that the same experiment can be associated with two different theories, as in the cases of Volta's disputes with Galvani and Sir Humphrey Davy.

Moreover, the results of this study correlate with those of Klassen (2009), where it was demonstrated that the relationship between Millikan and his postgraduate student Harvey Fletcher and the dispute between Millikan and Ehrenhaft over data collection and the interpretation of the results of the experiment for measuring the electrical charge provided undergraduate students with the opportunity to probe and reflect on the difficulties of Millikan's oil drop experiment. The students are now able to exhibit conceptions such as the quantisation of the electrical charge does not arise logically from the data of the oil drop experiment, but from the fact that Millikan collects the data and interprets them on the basis of his initial ideas of the data. Our results are also directly connected to those of Clough and Olson (2004) who argue that the use of short stories in combination with a scientific dispute as a strategy for teaching aspects of NOS can improve students' conceptions of these aspects.

Finally, as regards the third factor, the results of the students' responses after the teaching intervention empirically demonstrate that the strategy of teaching through short stories inspired by the history of the natural sciences works.

The advantages of this strategy appear to be the following: firstly, as far as possible these stories use the arguments, conceptions and thinking of the scientists themselves. As such, the dimension of the development of scientific knowledge is emphasised and not the 'final' version as it often appears in school textbooks. This leads to the second advantage, that the specific form of the short stories and the questions that accompany them make the discussion in the school classroom on all the aspects of NOS previously mentioned more dynamic and credible. The juxtaposition of the 'naive' and 'transitional' conceptions exhibited by the students prior to the teaching intervention with the features of these short stories appears to lead to the construction of new conceptions of these NOS aspects. Finally, a third advantage is the ability to apply this teaching strategy even in the context of traditional forms of education in the natural sciences without great changes to the curriculum, something that can encourage teachers to choose to teach NOS aspects in a more systematic way.

This study has shown that the use of a scientific dispute and the explicit incorporation of aspects of scientific knowledge into the scientific content of the lesson, through the use of short stories, improves students' conceptions of 'what is science' and 'how science operates'. General hypotheses on the educational material that was used and the change in the students' conceptions were also presented. The confirmation or contradiction of these hypotheses, however, could not be investigated with the methodological tools used in this study. This would require the use of another type of research methodology, namely classroom observation, and the research is currently proceeding along these lines.

## Appendix 1

Worksheet 3

*Short Story*

In his autobiography Millikan wrote that when the small oil drop was "*moving upward [in the electric field, against the gravitational pull] with the smallest speed it could take on, I could be certain that just one isolated electron was sitting on its back. The whole apparatus then represented a device for catching and essentially seeing an individual electron riding on a drop of oil.*"

And when the drop he was observing suddenly changed direction, he noted:
"*I had seen a balanced drop suddenly catch an ion*" from the air around.

Question: Which of the words that Millikan uses above could be characterised as indicating 'observation' and which 'inference'?
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
…………..

## Appendix 2

The Questionnaire

1. Scientists produce scientific knowledge (theories, laws). A part of this knowledge is to be found in the school physics textbook, which you yourself use. Do you believe that this knowledge (theories, laws) can change in the future? Answer 'yes' or 'no'. Explain why and give an example.

2. The diagram below shows that the atom is comprised of a nucleus at its centre surrounded by electrons that move around it.
   (a) Do you believe that scientists are certain about this structure of the atom? Answer 'yes' or 'no'.
   Explain why and give an example.
   (b) How do you believe that scientists determined this atomic structure?
3. Dinosaurs lived millions of years ago.
   (a) How do scientists kno§w that dinosaurs truly existed?
   (b) How were scientists able to determine what dinosaurs looked like?
   (c) Do you believe that scientists are certain about what dinosaurs looked like? Explain what makes them certain or uncertain.
   (d) Scientists agree that dinosaurs disappeared approximately 65 million years ago. Even so, scientists disagree as to the reason why. One group of scientists argues that a giant meteorite hit the earth 65 million years ago and led to a series of events which caused this extinction. One other group of scientists argues that a violent volcanic eruption is responsible for this extinction. How is it possible for scientists to reach different conclusions when they are all using the same data?
4. Scientists conduct experiments and research when they attempt to find answers to the questions they pose. Do scientists use their imagination and creativity during their research? Answer 'yes' or 'no'.
   (a) If no, explain why. Give an example.
   (b) If yes, explain why. Give an example.
5. In the early twentieth century two physicists, R. Millikan, professor at the University of Chicago and F. Ehrenhaft, professor at the University of Vienna, disagreed over the nature of the electric charge. Millikan argued that there is an elementary electric charge that is transmitted by a particle, the electron, and any other quantity of electric charge is an integral multiple. Ehrenhaft on the other hand argued that there are fractional electrical charges ('sub-electrons') and that a quantity of an electric charge can have any value whatsoever. In order to test their initial hypotheses the two scientists used similar experimental equipment and had the same experimental results, although each one believed that the experiment validated his initial hypothesis.
   (a) How was it possible for these two scientists to reach different conclusions when they were looking at the same data?
   (b) Is it possible to determine which of the two scientists was right? Explain your response.

## Appendix 3

See Table 1.

**Table 1** The aspects of the NOS evaluated by each of the items in the questionnaire

| Questions | Aspects of NOS |
|---|---|
| 1 | The empirical aspect of NOS |
| 2 | The empirical aspect of NOS |
| | The creative/imagination aspect of NOS |
| | The distinction between observation and inference |
| 3 | The empirical aspect of NOS |
| | The creative/imagination aspect of NOS |
| | The distinction between observation and inference |
| | The subjective aspect of NOS |
| 4 | The creative/imagination aspect of NOS |
| 5 | The subjective aspect of NOS |

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