Science & Education (2021) 30:381–408
https://doi.org/10.1007/s11191-020-00179-7

ARTICLE

Students' Views of Nature of Science

A Long-term Study

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Accepted: 3 November 2020 / Published online: 9 January 2021

Abstract
Nature of science (NOS) is considered an important aspect of scientific literacy. Despite efforts in guiding school students to develop more adequate NOS views, little is known about the long-term retention of students' post-intervention views. Retention of adequate NOS views is needed for functioning as scientifically literate citizens. Moreover, little is known about the long-term impacts of NOS interventions, important for evaluating their potentials in contributing to the preparation of scientifically literate citizens. This study reports on the results of four case studies through which the researcher examines the developments of four students' NOS views over a 13-year period. More specifically, the study sheds the spotlight on students' long-term retentions of their NOS views as well as the long-term implications of a NOS intervention. During the academic year 2006–2007, the researcher—a high school science teacher at the time—had designed and taught an Honors Biology course, using a consensus framework of NOS as its focus, contextualized within rich science content, and embedded within an explicit–reflective method. The researcher analyzed existing data from 2006-2007. He also collected and analyzed new data in 2019. The findings of these case studies show that the four students benefited from the NOS intervention in the short term, yet their patterns of retaining their NOS views were quite different in the long term. The results showed that it is not possible to assume that a NOS intervention with the characteristics described above and delivered within the setting of an Honors Biology course would necessarily have a long-term impact on students' views of NOS. The findings of this study are discussed in terms of *who* benefits from NOS instruction at the school level. Questions are generated and hypotheses are proposed for further investigation.

Keywords Case study · Nature of science · Retention · Scientific literacy · Social justice

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1 Introduction

Nature of science (NOS) is as an important component under scientific literacy (Lederman et al. 2013; Norris and Phillips 2003), which is a major goal of science education (Kampourakis 2019; Kolstø 2001; Laugksch 2000; OECD 2019). NOS refers to the epistemology of science, science as a way of knowing, and the values and beliefs inherent to scientific knowledge and its development (Abd-El-Khalick and Lederman 2000a; Lederman 1992). Scientifically literate individuals are said to make informed decisions at the individual and societal levels (Laugksch 2000). The latter is important from a democratic standpoint (Driver et al. 1996; Yacoubian 2018). In fact, developing informed understandings of NOS is important for making decisions on science-based social issues (Yacoubian 2015).

Despite efforts in guiding school students to develop more adequate NOS views, little is known about the long-term retention of students' post-intervention views. Retention of adequate NOS views is needed for functioning as scientifically literate citizens. Moreover, little is known about the long-term impacts of NOS interventions, important for evaluating their potentials in contributing to the preparation of scientifically literate citizens. This long-term study reports on the results of four case studies through which the researcher examines the developments of four students' NOS views over a 13-year period. Specifically, it describes how the students developed their NOS views over the course of a year-long intervention and examines the retention of those views 12 years after the intervention.

2 Theoretical Framework

The theoretical framework of this study draws upon three elements, namely consensus framework of NOS (Lederman 2004, 2007), explicit and reflecting teaching through contextualization of NOS instruction (Clough 2006), and retention of NOS views. In the sections that follow, I describe each of these elements, situate them within the relevant literature, and justify their application to the present study.

2.1 Nature of Science

For the purpose of this study, Lederman's (2004, 2007) NOS framework was used. Consensus frameworks, such as ones proposed by Lederman (2004, 2007) and McComas (2004, 2017), converge contentious philosophical debates into sets of NOS-related ideas that (1) reflect some level of generality of the characteristics of science, (2) show some level of agreement among various philosophical positions, and (3) invite learners to develop understandings about these ideas. One of the main arguments in favor of the consensus frameworks is its accessibility to school students. In other words, regardless of future career aspirations, all students need a basic understanding of NOS to be successful citizens and to participate in society (McComas 2020).

Lederman and his research group have developed a list of seven general aspects of NOS on which there is some consensus among philosophers, sociologists, historians of science, and science educators (Lederman 2004). Among these are the view that there is a distinction between observations and inferences; the idea that science is embedded in social and cultural contexts; the notions that scientific knowledge is tentative, empirical, and subjective; the view that scientific laws and theories differ; and the idea that science involves inference, creativity, and imagination.

The initiation of the current study goes back to the year 2006 and that explains the use of a consensus framework, Lederman's (2004, 2007) NOS framework in particular, as a basis for this study. Many science education policy and curriculum documents at the time also focused on consensus frameworks of NOS as educational goals and outcomes for K-12 students, such as *Benchmarks for Science Literacy* (AAAS 1993).

More recently, critics of the consensus frameworks problematize them for portraying a rather narrow view of science. Hodson and Wong (2014) argue for the need of a philosophically more sophisticated NOS model—one that is in harmony with the contemporary scientific practice and that authentically exposes learners to the diversity of its sub-disciplines. Allchin (2011) argues for the need of broader perspectives on NOS. He proposes "whole science" (p. 518) and maintains that NOS in school science should be sensitive to all dimensions of the scientific practice. Irzik and Nola (2011) criticize the consensus frameworks of NOS in school science for (1) portraying a rather narrow image of science, especially by excluding aims and methodological rules in science; (2) providing a uniform view of science and not being sensitive to the differences among scientific disciplines; and (3) lacking systematic unity. They borrow from Wittgenstein's notion of family resemblance and classify the characteristics of science under four categories: scientific activities, scientific aims and values, scientific methods and methodological rules, and scientific products. Erduran and Dagher (2014) argue for conceptualizing NOS through features that are unique or shared across scientific disciplines. Dagher and Erduran (2016) propose an expanded version of Irzik and Nola's (2011) model, placing emphasis on science as a cognitive-epistemic and social-institutional system. Finally, Kötter and Hammann (2017) recommend teaching controversies regarding the nature and function of science, arguing that controversy, rather than consensus, characterizes the cultures of disciplines such as history of science, sociology of science, and philosophy of science.

2.2 Explicit–Reflective Teaching Through Contextualizing NOS Instruction

In this study, explicit and reflective methods for teaching NOS were utilized. These methods assume the development of learners' NOS understandings to be planned learning outcomes, where learners engage in reflective thinking, guided by their teacher, to deepen their NOS understandings (Khishfe and Abd-El-Khalick 2002). In teaching NOS using consensus frameworks, many studies have reported that explicit and reflective approaches are more effective than implicit approaches in guiding learners develop more adequate views of NOS (e.g., Abd-El-Khalick and Lederman 2000b; Khishfe and Abd-El-Khalick 2002; Eymur 2019; Vhurumuku 2010; Yacoubian and BouJaoude 2010). Additionally, Mesci and Schwartz (2016) argue that instructional, motivational, and sociocultural factors may influence how students change their views about NOS aspects.

Moss (2001) reported on the results of a naturalistic study that focused on five students' NOS understandings tracked over a 1-year period. The context of the study was a Conservation Biology high school course. Most students had fully informed understandings of some aspects of NOS, including the tentative and empirical aspects, throughout the year-long intervention, that was hands-on and project-based, yet implicitly targeting students' development of NOS. The researcher reported that the students' NOS understandings remained mostly unchanged over the year. From another perspective, Burgin and Sadler (2016) conducted a study within the context of a research apprenticeship program where high school students worked at a research laboratory on an authentic research project. The researchers reported that explicit approaches were more effective, but some students experiencing implicit or reflective approaches did exhibit some gains in their NOS understandings. The researchers attributed these gains to the students' participation in a variety of methods that were employed in conducting scientific research, their contributions to the research team, and conversations that they had with their mentors.

Explicit and reflective teaching of NOS in this study took place through utilizing various platforms serving as contexts for students as they engaged in NOS learning. Examples included exploring historical cases, engaging in inquiry, and writing reflection papers. In fact, the literature supports the existence of a variety of effective contexts. For instance, Akerson et al. (2014) showed that a year-long contextualized explicit–reflective instruction was helpful with elementary students. Eastwood et al. (2012) reported that SSI contexts were effective for developing NOS understandings. Aduriz-Bravo (2014) had used short science stories based on history of science. Allchin et al. (2014) called for integrating historical cases, contemporary cases, and student-led inquiry investigations as complementary methods for teaching NOS.

Additionally, different scholars have used reflective writing as a means for engaging learners in NOS learning. Within the context of pre-service teacher education, reflection papers (Akerson et al. 2019; Demirdogen et al. 2016; Kinskey 2020) and reflective journals (Black 2006; Schwartz et al. 2004) are used in various contexts to guide the learners explore their NOS views. Many scholars have also used reflective writing in college science courses to guide the learners reflect on their NOS views, such as in the context of teaching Lewis Dot structure model for a college-level general chemistry class (Shultz and Gere 2015) and in the context of a community college evolutionary biology course (Scharmann and Butler 2015).

Finally, Clough's (2006) recommendations of contextualizing NOS instruction were taken into consideration in this study. Clough (2006) situates explicit and reflective NOS instruction along a continuum that includes decontextualized NOS instruction at one end and highly contextualized NOS instruction at the other end. Decontextualized NOS instruction targets developing NOS understandings that are isolated from science content, while contextualized NOS instruction targets developing learners' NOS understandings in parallel with science content. Bell et al. (2016) further illustrate Clough's (2006) continuum, by showing examples of how NOS lessons can range from having no to minimal, moderate, and high degree of science content. The researchers reported that using a content continuum to scaffold NOS lessons can be effective with pre-service teachers in developing their NOS understandings.

2.3 Retention of NOS Views

The literature on learners' retention of NOS views is scarce and often shows contradictory findings. In addition, with some exceptions, the focus of studies is mostly on short-term (months) rather than long-term retention (years) of participants' NOS views. For example, within the context of school science, Leblebicioglu et al. (2019) reported that grade 6 and 7 students developed and retained certain NOS ideas during a summer camp. These ideas were related to the multiple methods that can be utilized for doing research, differences between data and evidence, and questions guiding scientific research. Retention was tested 2 months after the intervention. Khishfe (2015) designed a NOS intervention for grade 10 students that focused on the tentative, empirical, and subjective aspects of NOS. A delayed post-test, 4 months after the intervention, was administered in the form of a questionnaire and semi-structured interviews. She reported that about one-third of the students retained the more informed NOS understandings but many others reverted to their naïve NOS understandings.

Studies utilizing contextualization of NOS instruction have shown some promise in terms of retention of participants' NOS views. However, unlike the present study which focuses on precollege students, most of those studies were conducted within the context of science teacher education. Akerson et al. (2006), for instance, reported that most of the 19 pre-service elementary teachers who participated in their study developed their NOS understandings throughout a science methods course as they engaged in explicit–reflective discussions on NOS. However, many of them reverted to their earlier inadequate views 5 months after the intervention.

Wahbeh and Abd-El-Khalick (2014) developed a NOS instructional intervention that integrated explicit and reflective approaches, rich science content, metacognitive learning strategies, and a conceptual change framework. The intervention was effective in improving in-service secondary science teachers' understandings of NOS aspects and subsequent retention 5 months after the intervention. It was also useful for the teachers to transfer their learning into NOS planning and instruction in their classrooms. The researchers reported that the successful transfer of the participants' learning of NOS into their classroom practices (especially as regards the empirical, tentative, and social-cultural NOS) was primarily mediated by the situatedness of the participants' NOS knowledge within the content, context, and experiences of the NOS intervention.

Another study by Herman and Clough (2016) and Herman et al. (2013) involved exploring science teachers' retention of NOS views and their NOS-related instructional practices 2–5 years after completion of a teacher education program. While still students, the teachers had taken a NOS course besides learning about NOS in other science education courses. The course engaged the pre-service teachers in exploring NOS through questions that were contextual and complex. Herman et al. (2013) reported that 12 of the 13 teachers taught NOS in their science classrooms. They also reported that six teachers had informed NOS understandings and six had transitional ones. However, having informed or transitional NOS understandings was not a factor in determining the level of implementation (high, medium, or low). Herman and Clough (2016) attributed the teachers' retention to the use of contextual approach. They also considered that teachers' continuous professional development after graduation could have also impacted retention of their NOS views.

Mulvey and Bell (2017) aimed at improving retention of NOS views through using a mixed contextualization approach, i.e., using a continuum of contextualized and non-contextualized NOS instruction. The continuum was based on the degree to which science content was explicit as a context for teaching NOS. The participants were 25 teachers in a professional development program. The teachers' initial inadequate NOS views were improved following the intervention. Moreover, most of the teachers retained their views 10 months after the intervention. The researchers attributed the retention of the teachers' NOS views to the use of a mixed contextualization approach. Additionally, they argued that compared to pre-service teachers, in-service teachers are at higher cognitive developmental positions.

2.4 The Present Study

To sum up, the present study utilized Lederman's (2004, 2007) consensus framework of NOS, embedded within explicit and reflective discussions, and implemented Clough's (2006) recommendations of contextualized NOS instruction. The focus was on the empirical, tentative, and subjective aspects of NOS. Even though Clough (2007) argues that consensus views fail to take into consideration the context and may lead students and teachers to appreciate NOS lists no more than declarative statements to be memorized, care was taken to avoid treating those NOS aspects as declarative statements. Instead, they were considered broad themes that were contextualized with the science content taught.

Additionally, unlike previous studies on retention of NOS views acquired through contextualized NOS instruction, the present study differed in its context, duration of intervention of the contextualized NOS instruction, and the period of retention of NOS views. In terms of context, this study focuses on precollege (secondary) level students in an Honors Biology course. The intervention comprised of contextualized NOS intervention took place over one academic year, and the long-term retention of NOS views was studied.

The unique context of this study is worth highlighting, considering that the students are usually high achievers and highly motivated in Biology, who take the course as an elective. This is important in terms of studying retention of the students' NOS views. The assumption is that high achievers and highly motivated students may have higher chances of retaining their NOS views compared to the average student in Biology at the secondary level.

It is also worth highlighting how the present study departs from that of Khishfe's (2015), considering that it is the closest to the present study in terms of studying retention of secondary students' NOS views. The participants in Khishfe's study were grade 10 students studying genetic engineering and water fluoridation, whereas the participants in the current study were grade 12 students enrolled in an Honors Biology course. Moreover, while Khishfe's intervention extended over 6 weeks, the intervention in the current study was over a full academic year. These differences are important to note considering Khishfe's results. She had reported that about one-third of the students had retained the more informed NOS understandings that they had developed because of the intervention, but many others had reverted to their naïve NOS understandings after 4 months. Khishfe postulated that such reversion could have been due to (1) the lack of sufficient connection between students' prior knowledge and newly acquired understandings of aspects of NOS, as well as (2) the short duration of the intervention. Considering the length of the intervention in the current study as well as the low number of students in the course, these two elements were restrained to the best possible. The current study also methodologically departs from Khishfe's study in that it utilizes multiple case studies, with the purpose of delving deeper into how the participants constructed their NOS understandings.

Furthermore, except for the study reported by Herman and Clough (2016) and Herman et al. (2013), where the retention of the learners' NOS views was assessed 2–5 years after the intervention, many of the studies cited above have evaluated the short-term retention of the learners' NOS views that ranged from 2 to 10 months after the intervention. To the best of my knowledge, the literature on long-term retentions of students' NOS views and long-term impacts of NOS interventions is scarce. Moreover, many of these studies are conducted with pre-service and in-service teachers rather than school students. It is important to evaluate the extent to which school students retain their NOS views in the long run, which they need for functioning as scientifically literate citizens. Additionally, studying the long-term impacts of NOS interventions is crucial for evaluating their potentials in contributing to the preparation of scientifically literate citizens who can participate in democratic decision-making. In the present study, a post-test was administered right after the NOS intervention and the same post-test was administered again 12 years after the intervention. The assumption was that at this point in their lives, the former students would be fully functioning in their societies as (hopefully) scientifically literate citizens. Twelve years was thought to be sufficient time for students graduating from universities, pursuing careers, taking new responsibilities in their personal lives, being active members in societies, and engaging in decision-making at personal and societal levels.

To sum up, the present study sheds the spotlight on students' long-term retentions of their NOS views as well as the long-term implications of NOS interventions that are based on consensus frameworks and use a contextual approach to teach NOS, embedded within an explicit–reflective method. The research questions of the current study were as follows:

1. How do students' NOS views develop within the setting of a grade 12 Honors Biology course, in which a consensus framework and a contextual approach embedded within an explicit–reflective method are used?
2. To what extent are the students' NOS views retained 12 years after the intervention?

3 Method

The present study pursued a qualitative design where multiple case studies were utilized. A case study is an intensive, holistic description and analysis of a bounded phenomenon such as a person, a program, an institution, a process, or a social unit (Merriam 1998). Creswell (2007) considers case study research a qualitative approach in which the researcher explores bounded system(s) using multiple data sources and collecting in-depth data. For the present study, four former students were considered the four cases.

3.1 The Honors Biology Course

During the academic year 2006–2007, the researcher was a high school Biology teacher at a private school in Lebanon. He can be described as a participant observer who taught the course as well as collected and analyzed all the data. During that academic year, he designed and taught a grade 12 Honors Biology course. The school catered local and international students with diverse nationalities and coming mostly from families of middle to high socioeconomic status. According to the school policy, all students had to take one Biology course at the secondary level. Some high achieving students who were motivated in Biology could choose to take Honors Biology as an elective after successfully completing their mandatory Biology course.

At the time, the teacher had an MA degree in Science Education and his MA thesis involved research on NOS teaching and learning. Using his prior knowledge and experience, he designed the Honors Biology course using a consensus framework of NOS as its focus. He also engaged in a self-motivated action research with the goal of improving his own practice. The school encouraged its teachers to conduct action research as a means for professional development. Therefore, at the time there was no intention to publish results.

The Honors Biology course was designed for students who demonstrated high level of performance in Biology. It consisted of an in-depth study of cellular and molecular biology, genetics, evolution, and diversity of living things. Students met 5 hours per week for the entire academic year and engaged in inquiry-based learning in the class as well as in the Biology lab.

The teacher used Lederman's (2004, 2007) framework to engage the students in explicit–reflective discussions on NOS. In every unit, the teacher included NOS-related objectives that were explicitly addressed in the classroom. The NOS-related objectives were aligned with the science content to be taught. For example, in the unit on "Diversity of living things," the teacher provided inquiry experiences for the students, where they also had the chance to engage in explicit–reflective discussions about certain aspects of NOS. In one lesson, the teacher engaged the students in a hands-on activity that involved classifying insects. The activity became a context to engage the students in exploring different scientific methods as well as the empirical aspect of NOS. The teacher guided a discussion where the students reflected on the methods used by biologists to classify living things. The students reflected on observational studies, within the context of the science content that they were studying, and compared them to the experimental method that they were familiar with. They also explored how evidence is generated in observational studies. The role of the teacher was to facilitate the discussion through posing questions, making the target NOS aspects explicit, and guiding the students to master the NOS objective in question. Using Bell et al.'s (2016) context continuum, it could be considered a moderately contextualized NOS instruction.

Another example of a NOS-related objective in the "Evolution" unit involved reflecting on the history of the evolutionary theory and identifying how different scientists had contributed to the current understanding. This objective led to highly contextualized NOS lessons, to use Bell et al.'s (2016) terms, where the students engaged in learning about history of science and also reflected on NOS, such as the tentative and subjective aspects. The NOS intervention involved the teacher guiding a discussion on the historical developments of the evolutionary theory and focusing on the work of Lamarck, Darwin, Hardy and Weinberg, and Peter and Rosemary Grants. The work of these scientists was already the focus of the sessions during that week. The teacher asked the students to discuss how previous research helped each scientist to do their work, discuss how the background of each scientist was important in their work, analyze the different ways by which these scientists have performed their research, etc. The teacher's role involved asking questions and guiding the students to engage in a reflective discourse, while making the NOS aspects in question explicit. The teacher's lesson plans showed that throughout the year most of the NOS teaching was moderately contextualized or highly contextualized.

The students were also engaged in reflective writing about their NOS views after every unit. For example, at the end of a unit on the cell theory, students were asked to write a reflection paper in which they had to reflect on the development of the cell theory through an analogy of their choice that could help them explain how science works. The teacher provided feedback on their writing and inserted comments and questions in the margins. The feedback aimed to help the students reflect further on their NOS understandings and address them in their subsequent papers.

3.2 Participants

The targeted participants were the former students who were enrolled in the Honors Biology course in 2006–2007. All nine students who took Honors Biology graduated that year from the school and were enrolled at institutions of higher education in Lebanon or abroad. Twelve years later, the researcher approached the former students through social media (Facebook) and invited them to participate in the study. He could recruit four of them. These four students presented similar characteristics as the other students in the Honors Biology class in terms of their academic achievement and motivation. The researcher secured consent from the four former students to use their previous work as data and collected additional data from them.

The first former student, Sam (pseudonym), was a highly motivated student in Biology and a high achiever. After graduating high school, he moved to the USA and completed an undergraduate degree in Molecular Biology, with a minor in Chemistry and another one in Philosophy. After working as a clinical analyst for 2 years, Sam was admitted to medical school at a university in the USA. He graduated with an MD degree. At the time of data collection, he was a resident, specializing in Emergency Medicine.

The second former student, Sue (pseudonym), acquired an undergraduate degree in Psychology from a university in Lebanon as well as a Diploma in Special Education. In her undergraduate years, she took four science courses, namely Introduction to Biology, Basic Chemistry, Advanced Chemistry, and Physiology of the Brain. After graduation, she worked as a teacher for a few years in Lebanon and Saudi Arabia, she even taught some science at the elementary level. Then, she got married and had children and the family immigrated to the USA. She is currently an elementary teacher at a public school.

The third former student, Mike (pseudonym), was a highly motivated student in Biology. After graduating high school, he studied Computer Science at a university in Lebanon and obtained a BS degree. He worked for a network company for several years. At the time of data collection, he had recently completed an MS degree in Computer Science, which he had pursued after being employed for several years.

The fourth former student, May (pseudonym), was a high achiever in Biology. She acquired a BA degree in Management from a university in Lebanon after which she sought employment in the United Arab Emirates. She shifted among various jobs. At the time of data collection, she was working as an event organizer at a hotel.

3.3 Data Sources

For phase 1 (2006–2007), data sources included a questionnaire, entitled "Perspectives on Scientific Epistemology" (POSE) (Abd-El-Khalick 2002), which was administered to students as a pre-test at the beginning of the academic year (September 2006) and as a post-test at the end of the academic year (June 2007). Following Saldana (2003), the pre-test was considered baseline data for this long-term study. Additional data sources included the students' written assignments, such as reflection papers, as well as the teacher's comments on those assignments, in addition to his notes and reflections found in his "lesson plan book." The researcher had access to all this data from that time and analyzed them after securing IRB approval.

Twelve years later, the researcher analyzed the existing data from the teacher and the four students. In addition, he collected new data from those four students. As part of the case studies, and considering the qualitative nature of the study, description of the profiles, the 13-year academic journey, and the different experiences of each student was asked and recorded.

For phase 2 (2019), data sources included the same POSE questionnaire, which was administered to the former students as a delayed post-test, as well as individual in-depth, semi-structured skype interviews with each of them. Each interview took about an hour. The interview questions were tailored on the responses that each participant provided to the questions of the POSE questionnaire. The interviews were also a chance for guiding the participants to reflect on their responses provided 13 years ago and reflecting on the growth that they went through (life experiences, academic and work experiences). The interview questions were prepared after the responses to the POSE questionnaires were received. Interviews were audio-recorded and transcribed. Phase 2 data collection took place in summer 2019.

The participants were provided as much time as they needed to answer the questions of the POSE questionnaire. In phase 1, they completed the questionnaire handwritten within the context of the classroom, while in phase 2, they completed it remotely and sent it back electronically.

3.4 Data Analysis

The students responded to the POSE questionnaire three times (in 2006, 2007, and 2019). Yet, all the data was analyzed in 2019 by the researcher. The responses to the POSE questionnaires were analyzed using Abd-El-Khalick's (2002) guidelines. The present paper focuses specifically on the development of the students' views of the tentative, empirical, and subjective aspects of NOS. Individual profiles were constructed for each participant. Accordingly, each student's views of the target NOS aspects were classified as inadequate, partially adequate, or adequate based on the provided responses on each of the three POSE questionnaires.

The researcher also qualitatively analyzed other data from phase 1 (students' written assignments) and interviews from phase 2 in 2019. The qualitative data from phase 1 helped trace the year-long developmental journey, i.e., the time elapse between the pre-test and the first post-test. It helped understand how the students' target NOS views evolved during the NOS intervention. The qualitative data from phase 2 helped trace some of the life, academic, and work experiences of the former students over a 12-year-period, i.e., between the first post-test and the second post-test. It helped outline how the students' target NOS views further evolved after their graduation from school. It is worth noting that the qualitative data from phase 2 did not provide direct evidence to explain the relationship between students' NOS views right after completing the Honors Biology course and 12 years later. This is because many events could have affected shaping their new NOS views. However, the analysis was helpful to raise hypotheses for further research. All qualitative data was coded, patterns were identified and themes generated, using Miles et al.'s (2014) approach. Triangulation of data took place through consulting multiple data sources.

The final reporting included the generation of a chronological narrative for each former student that focused mainly on the NOS aspects that are targeted in this study. The four cases were examined through explanatory and descriptive lenses (Cohen et al. 2018). The four cases were also compared to each other in generating conclusions. There were no generalizations made from this study, but there were a number of hypotheses and questions raised that can be pursued in future studies.

4 Findings

4.1 Former Student 1: Sam

4.1.1 Tentative NOS

Before starting the Honors Biology course, Sam had an inadequate view about the tentative aspect of science. He believed that "facts and laws will not change in the future because they have been proven in all ways" (Pre-test 2006). He thought that the only forms of knowledge that can change are scientific theories, which can become unchangeable laws based on "more information, knowledge, research, and evidence" (Pre-test 2006).

The first instance where the teacher has challenged this view is evident in a reflection paper written in November 2006, in which Sam analyzes the historical developments of the cell theory. He had claimed, "Data collected from the 1660s until almost 200 years later, the cell theory was completed. We don't have a law yet so we expect the cell theory to continue changing." The teacher had commented, "What is the difference between a scientific theory and a law? Can a theory become a law? Let's discuss this in class next week" (Reflection paper, November 2, 2006).

It is not possible to know from the data how Sam's view of the tentative aspect of NOS developed over time. Almost a year later, his answers on the post-test show an adequate view of this aspect. He writes:

> Science is always changing. New evidence as well as new ways of interpreting evidence always arise, forcing science to change (Post-test 2007)

Twelve years later, Sam has retained his adequate view of the tentative aspect of NOS. He writes:

> …If we choose to define it [scientific knowledge] as our total understanding, then I do not see how we can believe that it would not change. One area in particular where we continue to learn and refine our understanding is how best to treat cancer… (Post-test 2019).

During the interview, the researcher asked Sam to reflect on his view of tentativeness of science and how that was shaped throughout the years. The researcher also showed him responses he had written in the Pre-test (2006) and the post-test (2007).

Sam claimed that one thing that he remembers well from the Honors Biology course is the distinction between scientific theories and laws. He thought he knew about the distinction, but shortly after starting the course, he realized that he did not. He kept reflecting on it all the time, even after graduating high school. He commented on his response on the post-test (2007, see above). He said,

> Even though it is true that scientific knowledge changes based on abandoning old theories and replacing them with new ones as needed, what I had written back then is too strong. Sometimes we shape things rather than completely changing them. Because we have a large number of scientists doing research today and because of the technology available, it is less likely that theories will be abandoned completely, even though there is always the possibility. (Interview Summer 2019).

4.1.2 Empirical NOS

Sam appreciated the role of direct and indirect evidence in the formation of scientific theories. While asked about the existence of dinosaurs on the pre-test and before starting the course, he highlighted the role of fossils as an indirect evidence for their prehistoric existence.

> Dinosaurs existed and can be proven because of the fossils and bones. Carbon testing can also see how old the bones are proving there prehistoric existence... [Scientists are] not too certain [in how dinosaurs look like]. (Pre-test 2006)

Nonetheless, considering that he viewed scientific laws and facts as being absolute, he underestimated the role of evidence in abandoning scientific laws and facts and replacing them. He claimed, "Evidence serves for reinforcing facts and laws. The more evidence the stronger the laws and facts become" (Pre-test 2006).

Perhaps his initial challenge to view scientific facts and laws as subject to change was conducive to his inability to fully appreciate the empirical aspect of NOS. This was not a challenge anymore as he made progress in the course. In fact, Sam's responses on the post-test a year later show that he had developed an adequate view of the empirical aspect of NOS. He claims that scientists know that dinosaurs really existed from "fossils, amber, imprints, bones of prehistoric dinosaurs." They are "pretty certain" in how dinosaurs look like "because DNA is substantially concrete evidence. However, new evidence and new ways of analyzing that evidence may produce different results. Science is always changing" (Post-test, 2007).

Nonetheless, his initial challenge to view scientific facts and laws as subject to change can be at least partly attributed to his initial views of the nature of truth, which was eventually changed. The reflection papers that he had written throughout the year show a progression of those views. For example, in a reflection paper written in November 2006, he had claimed:

> Information is already out there, waiting to be discovered. The process of photosynthesis was out there 1000s if not 1000000 of years ago, and is now nearly fully understood (Reflection paper, 18 Nov. 2006)

A few months later, it seems that Sam had changed his view on how scientists try to understand truth. He has moved away from a notion of "discovery" to one that involves "making sense" of the surrounding rather than finding the truth. Within the context of a reflection paper on historical developments of the Evolutionary thought, Sam writes:

> Over the past 100s, if not 1000s of years, science has been modified to fit into a puzzle. From Aristotle, to Bacon, to Darwin and present day scientists, science is being changed to make sense and understand nature… (Sam, Reflection paper, March 23, 2007)

Twelve years later, his response to the questionnaire showed an adequate view of the empirical aspect of NOS and a thorough understanding of the nature of truth. He wrote:

> Evidence means there is some level of objective information that can be used to support a claim… Based on the structure and morphology of bones, teeth, skull scientists are able to construct a superficial image of dinosaurs… (Post-test 2019)
> and
> … Scientific principles – regardless of whether they are in the form of facts, laws, or theories – exist and will continue to exist irrespective of human awareness… how do scientists discover scientific knowledge? In the most basic sense, it is simply by trial and error and incorporating what is already known (Sam, Post-test, 2019)

During the interview, Sam attributed his advanced understanding of the nature of evidence to his experience in emergency medicine. He said that as a practitioner he reviews the existing evidence quite a lot. He thinks that with time he developed a critical view of evidence and what it means. He believes he is a reflective practitioner and that reflection is key to his growth as a medical doctor.

As for his understanding of the nature of truth, he clarified that as part of his undergraduate philosophy courses, he had developed a view that there is absolute and relative morality. However, he thinks there is only absolute truth. He explained that quarks existed even if we did not know about them. However, considering that language is important for theory building, then theories are partly subjective. Nevertheless, theories are explanations that help us make sense of the truth.

4.1.3 Subjective NOS

Before starting the Honors Biology course, Sam believed that scientists think in different ways. In explaining how scientists use the same data and still arrive at different explanations regarding the cause of extinction of dinosaurs, he claimed that "[i]t is impossible for all the scientists to think in the same way. Because of our difference in imagination or hypothesis, there is going to have to be difference in thought" (Pre-test 2006). This is in fact an adequate view of the subjective aspect of NOS. Sam maintained his adequate views of the subjective aspect of NOS not only during that year when he took the Honors Biology course but also over the next 12 years.

> I believe some models must be made if we are to use it and build on it…. Better to build and rebuild than not build at all… Scientists will continue to disagree because we all think differently, and scientists look at data and evidence through different ways. (Post-test 2007)
>
> It's all about the interpretation of data. Even though data is objective, our interpretation is easily influenced by our mindset and our biases… (Post-test 2019)

Finally, during the interview, the researcher had a discussion with Sam about how important it was for him to have learned NOS in the Honors Biology class.

> Sam: I benefited from the discussions both as a person and as a medical practitioner after years.
>
> Researcher: Can you give me an example of how NOS learning was useful for you as a citizen?
>
> Sam: A few years ago, there were some people who wanted evolutionary biology to be removed from the science curriculum at schools in Texas and Florida. I thought this was not a good idea because you can teach kids evolutionary biology and religion at the same time. They are different kinds of knowledge. I also thought that evolution makes us understand everything in Biology. So I was against that idea as a citizen.
>
> Researcher: What about an example as a medical practitioner?
>
> Sam: As a medical practitioner, NOS helped me better understand the nature of evidence, how to consume the research literature, and how to interpret conclusions and direct my practice.

4.2 Former Student: Sue

4.2.1 Tentative NOS

Before starting the Honors Biology course, Sue had an adequate view of the tentative aspect of science. She believed that "someday a scientist may discover something new that will cancel or prove wrong an old law or theory that already exists…" (Pre-test 2006). Her view of tentativeness remained stable throughout the year. For example, in a reflection paper Sue writes:

> [Scientists] may either be based on an old discovery and try to add on, or they may try to come up with a new explanation for why something happens. (Reflection paper, November 3, 2006).

After a year, Sue shows quite a comprehensive view of tentativeness. She writes:

> … New discoveries lead to new information. Sometimes a law/ theory could be modified, sometimes pieces are added to it, and still other times parts could be proven wrong and changed completely. (Post-test 2007)

After 12 years, Sue's view of tentativeness was still intact.

> Scientific knowledge will likely change in the future because the more scientists explore the more they learn and discover new things. Scientific discovery is an ongoing process. New data might be discovered that could either approve or validate something different than what we have learned in our textbooks. (Post-test 2019)

During the interview in Summer 2019, when asked about how she has developed her view of tentativeness in science, Sue clarified that she considers the idea being connected very well with her personal beliefs about life. She explained that change has been an integral component of her life since childhood and that her experiences have taught her that "everything keeps changing in life, sometimes change makes us improve our behaviors and sometimes we adapt to change by changing our behavior."

4.2.2 Empirical NOS

Sue's journey of how she viewed the empirical aspect of NOS started in 2006 with a belief that science relies entirely on direct observations with no room for inferences. In the pre-test, Sue claimed that bones and skeletons of dinosaurs are evidence for their existence. However, scientists cannot tell how they looked like because "there is no actual evidence found" (Pre-test 2006).

The first piece of evidence that shows an intervention from her teacher goes back to a reflection paper that she had written in March 2007. Within the context of reflecting on the age of the Earth, Sue had claimed "scientists made it possible for us to know that the Earth is millions of years old." The teacher had challenged her with a side note stating, "Were scientists alive millions of years ago? How do they know the age of the Earth?" (Reflection paper, March 23, 2007).

In subsequent papers, Sue was able to change her partially adequate view of the empirical NOS. In a reflection paper on genetics written in May 2007, she claims "scientists do not need to see something in order to prove. For example, biologists did some experiments and then developed a model for how the DNA looks like. No one ever saw it." (Reflection paper, May 8, 2007). The post-test shows that she has developed an adequate view of the tentative aspect of NOS. She writes:

> Fossils found throughout the world prove that dinosaurs once existed. Based on the knowledge scientists have about the world 65 million years ago, they are able to infer what dinosaurs looked like. Example, if scientists know the weather was really hot at that time, they may infer that dinosaurs skin is rough. (Post-test 2007)

Sue's view of the empirical NOS reverted during the subsequent years. Her answer to the exact same question 12 years later shows that she has the same view that she held before starting the Honors Biology course. She writes:

> I believe that it is hard to say which group of scientists is right because there is no evidence to prove which explanation actually happened. Both are possible explanations but neither have been proven 100%. No one existed at the time to actually see what happened. (Post-test 2019)

During the interview, Sue claimed that "interpretation in science is important but less than evidence". She added that "interpretations are based on scientific knowledge and they are done by scientists who have authority, that's why those interpretations become important… but evidence is one." For Sue, there was an overlap between evidence and truth. When asked to discuss the relationship, she mentioned that "evidence is truth and there is only 1 truth."

The researcher asked her to read parts from her reflection paper that she had written in May 2007 as well as her answer to the same question that she had answered in the post-test 12 years ago and which showed adequate views of the empirical aspect of NOS. The researcher asked her to reflect on her previous answers, comparing them to her current position.

Sue claimed that she does not remember much of the NOS discussions held in the Honors Biology class. She also highlighted that NOS discussions were never a priority for her at that time. However, she has retained some of that information because the classes were very interactive and she had enjoyed them. She also admitted that she never thought about NOS after graduation, whether as part of coursework at the university or in her everyday life. She added, "As a citizen, as a teacher, and as a parent I am not involved with science in any way" (Interview 2019).

4.2.3 Subjective NOS

Initially, Sue held an inadequate view of the subjective aspect of NOS. For her, scientists can have different points of views and that explains why they may disagree in their explanations. Her answers revealed a lack of a connection between scientists' points of views and scientific evidence. She writes in the pre-test:

> Scientists can disagree [in their representation of the atom] because no one has actually seen an atom. They have different point of views. Everyone does have their own opinion. (Pre-test 2006).

Within the context of a reflection paper on the composition of matter written in October 2006, Sue had claimed that "Democritus and scientists today have different opinion about the atom. Democritus thought that all matter is made up atoms that are indivisible. Scientists today think that the atom can still be divided into subatomic particles." The teacher had challenged her notion of "opinion" through a side note that stated, "What is the basis of the different opinions? Were the methods used by Democritus and contemporary scientists similar?" (Reflection paper, October 25, 2006).

Gradually, Sue's view of the subjective aspect of science became more adequate. In a paper written within the context of a unit on cell growth and division, Sue had claimed that "scientists nowadays can control the growth of certain cancer cells" and that "different doctors try different approaches to cure cancer. This is because they have different experience with dealing with cancer" (Reflection paper, January 12, 2007). In fact, this was the first instance where Sue's view of subjectiveness in science had moved away from pure opinions to focus on some sort of experience. In fact, Sue never developed an adequate view of the subjective aspect of NOS throughout the Honors Biology course. The subsequent reflection papers that she had written included interpretations of subjectivity primarily based on scientists' historical era and experiences, but never from a perspective of their different theoretical backgrounds. This is in spite of cues and side notes by her teacher encouraging her to think differently.

Twelve years later, the post-test and the interview show that Sue has reverted to her initial inadequate view of the subjective aspect of NOS. She writes:

> … scientists interpret the evidence differently. Their interpretations are based on what they think or believe not on actual data presented. (Post-test 2019)

During the interview, she claimed that "every human being has an opinion and scientists are humans." For her, "opinion in science is important" and that "opinion is in the interpretations that scientists make and that's why evidence is more important than their subjective interpretations" (Interview 2019).

4.3 Former Student: Mike

4.3.1 Tentative NOS

Initially, Mike believed that scientific knowledge is unchangeable, even if new knowledge could be developed. This inadequate view of the tentative aspect of NOS was well reflected in the pre-test and the first writing assignment that he had developed. He thinks that "[a]fter obtaining specific results, scientists can come up with a conclusion which does not change" (Pre-test, 2006), even though "in science; there is no ultimate defined knowledge, because science is huge world that is boundless" (Reflection Paper, Nov. 3, 2006). In subsequent writing assignments, Mike starts changing his views. Reflecting on the historical developments of photosynthesis, he wrote:

> Jan van Helmont concluded that most of the mass the plant has gained came from water after testing the increase in mass of a small tree, because it was the only factor he changed from time to time. Later research proved that he was wrong and showed that carbon dioxide in the air was responsible for most of the mass of the tree. (Reflection paper, Nov. 20, 2006).

The teacher had written a comment next to this paragraph, asking Mike to reflect on how science changes: "What does this mean about how science works: is scientific knowledge fixed? I would like to read more about it in your next reflection paper?" (Reflection paper, Nov. 20, 2006).

There is some evidence in subsequent papers that Mike had developed a partially adequate view of the tentative aspect of NOS. This is evident in a paper written in March 2007:

> … Many scientists today might not agree on Darwin's theory or on a part of the theory. If in the future, new studies and research proves the opposite of Darwin's theory, then it might change the scientific knowledge. But that seems imaginary in reality. For example, modern evolutionary studies are primarily based on Darwin's theory. (Reflection paper, March 23, 2007).

Even though Mike acknowledges that scientific knowledge changes, he is strongly convinced that change in the sense of replacing old scientific claims with new ones is "imaginary." This is further confirmed in his post-test:

> Technology advances through the years, and new techniques lead to new developments in the field of science. I believe that better explanations of phenomenons can give a more thorough understanding of life… Laws give a final claim, while theories have higher tendency to change (Post-test, 2007).

In summer 2019, Mike's response on the same post-test question shows that he has maintained his partially adequate views of the tentative aspect of NOS. He writes:

> Scientific knowledge changes as with new skills and advanced technology scientists can have access to further details needed for explaining scientific phenomena in a more thorough way. Old theories can be

> improved because of the details. New knowledge can be added because of the invention of new theories and laws. (Post-test, 2019)

During the interview, there was a conversation about the tentative aspect of NOS. Mike insisted that old scientific knowledge can only be improved and never abandoned. Even when cued by the researcher, he maintained his partially adequate views.

4.3.2 Empirical NOS

Mike initially held a partially adequate view about the empirical aspect of NOS. Even though he highlighted the importance of evidence in science, he did not link it to the rejection or modification of scientific knowledge. When discussing about how certain scientists are about the way dinosaurs looked like, in the pre-test he claimed that "Scientists are very certain about how the dinosaurs looked like because they have evidence. Fossils indicate the existence of dinosaurs in 65 million years ago. DNA samples are then analyzed to predict the species… Scientists predict their structure based on found results. They have proof. They cannot be wrong." (Pre-test, 2006).

In a reflection paper dated November 3, 2006, Mike draws an analogy between the construction of a building and the development of the cell theory. In this analogy, he claims that unlike a building, which has a finished form, the cell theory "never has an utter form, because the cell theory develops throughout the years and changes when new research reveals new evidence of the cell." The teacher has put a note next to this paragraph, encouraging Mike to further reflect on this analogy in his next paper. The note reads:

> I like your analogy, Mike. Can you reflect in your next paper how in light of new evidence a scientific theory such as the cell theory "develops" and "changes" as you mention? (Reflection paper, November 3, 2006).

There is some evidence in subsequent papers that Mike has tried to make a connection between evidence and change; however, change is always in the sense of improving already-existing scientific claims. This is also evident in the post-test in his response to the same question about dinosaurs. He writes:

> Scientists are certain enough [about the way they believe dinosaurs look like] as long as they trust the computers and scans that they use and as long as evidence permits to generate conclusions from the fossils that they discovered through archeological sites. They may change their mind with new computers or new evidence and with time provide better image of dinosaurs. (Post-test, 2007)

In summer 2019, his response to the same question reveals that he has maintained his adequate view of the empirical aspect of NOS. He writes:

> Scientists are somehow certain [about the way they believe dinosaurs look like] based on the fossils that they analyze. The technology that they use improves with time which improves their analysis and results. They can develop new description of how dinosaurs look like based on the new results and evidence. (Post-test, 2019)

4.3.3 Subjective NOS

Initially, Mike had an inadequate view of the subjective aspect of NOS. For him, scientists have different opinions in explaining data. When asked about how scientists having access to and using the same data arrive at different conclusions, he gave the following example: "… Scientists have different opinions on the results. For example, a T-Rex might have skin colors of red and brown. Others might say that skin color changes throughout the seasons. It can't be proven." (Pre-test, 2006). He also explained that "scientific opinion is what a scientist thinks of a topic based on assumption." (Pre-test, 2006).

In a reflection paper written in November 2006, Mike claims that "scientists can't be subjective and infer from their observations based on their personal feelings and thoughts." (Reflection paper, November 20, 2006).

Mike was able to change his view of the subjective aspect of NOS over time. In April 2007, he had read Charles Darwin's *The Origin of Species* and had written a paper in which he had summarized the book and reflected on two ideas. In the paper, Mike shows the uniqueness of Darwin's work. For example, he discusses how Darwin's work was different from others before him as well as his contemporaries. He claims that "Like many great scientists, Darwin did not invent his theory from the ground up, rather, he seized upon earlier research to create a comprehensive and defendable theory" (Summary paper, April 15, 2007).

This is the first instance, as evident from the data, that the teacher encourages Mike to reflect on his earlier claims about the subjective aspect of NOS. As a side note, the teacher writes, "So, how important was Darwin's theoretical background in shaping his theory? What does this show about how science works?" (Summary paper, April 15, 2007).

In the post-test, Mike shows an adequate view of the subjective aspect of NOS. Within the context of reflecting on a model of an atom, Mike claims that "…scientists can theoretically create a model to meet their purpose… Depending on scientists' background and available theories of their time, theories of the atom can have different models. Groups of scientists either agree or disagree with those models" (Post-test, 2007).

Interestingly, 12 years later Mike's view of the subjective aspect of NOS is not as adequate as it was. In summer 2019, his response to the same question does not highlight the role of a scientist's theoretical background in shaping her work. He claims:

> I'm not sure if I remember the atomic theory, but there were different theories over the course of history… Scientists had different explanations about how atoms looked like and their explanations reflected what was available at that particular time in history." (Post-test, 2019).

During the interview, the researcher had the chance to engage Mike in a discussion about the subjective aspect of NOS. Here is an excerpt that was taken from the interview:

> Mike: Different periods of time in history have made scientists to have different priorities. For example, today with the technology available, scientists can examine details that other scientists could not examine before.
>
> Researcher: If it's a matter of only technology used, how do you explain that different contemporary scientists can have different explanations when using the same technology and looking at the same data set?
>
> Mike: There should be one correct answer. Maybe some scientists are doing mistakes or are not well prepared to handle the technology.
>
> At this stage the researcher shows Mike what he had written twelve years ago within the context of Darwin's summary paper and the post-test question on atomic theory and invites him to reflect.
>
> Researcher: Do you agree with what you had written twelve years ago?

> Mike: Maybe. I remember we discussed Darwin's theory in class and how he was influenced by other scientists.
> Researcher: You have a good memory. Then you claim that the scientists' background and theoretical background is important for shaping new knowledge. What do you think about that?
> Mike: Now I feel like we're in class again.
> Both start laughing
> Researcher: Can you reflect on what made you change your mind over the years?
> Mike: I remember discussing about these things with you when I was in grade 12. I forgot them. Maybe I never thought about them after that. (Interview, summer 2019).

As a student in computer science, Mike never had the chance to reflect on NOS with his professors and fellow students. He claimed that while doing his Bachelor's degree, "there was heavy focus on content and technical skills." Later on, he never thought about NOS as well. "The kind of job that I pursued in the company in which I worked for several years was very technical in nature, giving me no chance to think like a scientist." When asked about using NOS as a citizen, he said these kinds of discussions were "irrelevant in my everyday life" (Interview, summer 2019).

4.4 Former Student: May

4.4.1 Tentative NOS

Initially May had an inadequate view of the tentative aspect of NOS. She believed that scientific facts and laws are unchangeable, even though new knowledge could be developed. She writes:

> … [S]ome of the information we have can change in the future when another machine or technology created will open a new window for us and gives us more scientific knowledge and more information on the world around us… However, all facts and laws will never be changed or proven to be wrong… no matter how much technology and new machines there are… (Pre-test, 2006)

It does not take long for May to start questioning her own view of tentativeness in science. In a reflection paper written in November 2006, she draws an analogy between the development of the cell theory and that of the step pyramids. Her analogy shows how puzzled she is with the notion of tentativeness. She moves back and forth trying to find an equilibrium but she fails. In this 1000-word essay, she initially makes the argument that "each level of the pyramid that's on top of the first are just an addition to almost finishing the pyramid. Each level can be compared to a scientist and his theory" (Reflection paper, November 3, 2006). Clearly, May defends here an additive nature of change. But then later in the same paper, she claims that change can take place in science unlike the step pyramid. She ends her paper with the following idea:

> Science is a very tentative thing; everything can change in an instant. The step pyramid is a structure that can never be altered. So, I guess, when it comes to comparing a scientific theory to something, this something should be something that might change in the future… (Reflection paper, November 3, 2006).

Next to this paragraph, the teacher has written a note in which he has encouraged May to keep thinking more about how science changes and write about it in the subsequent papers.

A few weeks later, May goes back to her initial view of tentativeness. In a reflection paper on the historical developments of photosynthesis, she writes:

> The science of photosynthesis has been changing throughout the years. In one experiment, we saw that the plants produce oxygen in the presence of sunlight. In another experiment, we saw that plants convert light energy into chemical energy. The concept is not changing, but more details are being added to a broad process…" (Reflection paper, 18 Nov. 2006)

Parallel to her inadequate view of tentativeness, it is evident that May believes in an absolute truth out there and the goal of science reaching that truth. She writes:

> Science is ever-changing; we cannot know the complete truth about something. But sometimes we can get close to knowing or understanding more about the world around us. (Reflection paper, January 20, 2007)

At that point, the teacher has commented through a side question: "What if one day a group of scientists come up with a completely different discovery which makes more sense and what if other scientists agree on the new discovery? What would happen then?" (Reflection paper, January 20, 2007).

Two months later, in March 2007, within the context of a reflection paper on evolutionary biology and after analyzing various theories of evolution that had existed before Darwin, May seems to have developed an adequate understanding of tentativeness, one that underscores abandoning certain claims and replacing them with others. This is the first instance where May shows evidence of a more adequate view of the tentative aspect of NOS. She considers science to be "a very fluctuating and changing subject. Ideas and theories that were once proven as true two hundred years ago may be considered as incorrect today" (Reflection paper, March 23, 2007).

Analysis of May's responses to the POSE questionnaire shows that based on a year-long intervention she had developed an adequate view of the tentative aspect of NOS. She claims that "[w]ith new evidence all the scientific knowledge can change. If this new evidence can prove a theory or law to be wrong, then scientific knowledge will change" (Post-test, 2007).

Interestingly, 12 years later, May has reverted to her initial inadequate view of the tentative aspect of NOS. In summer 2019, she believes that "[t]here are certain facts in science that do not change… Scientific knowledge changes because there are always new discoveries. We know more today than in the past." (Post-test, summer 2019). During the interview and based on May's responses to the POSE questionnaire, the researcher asked her why she thinks "there are certain facts in science that do not change". Her immediate response was that "scientists are confident today because of what they have accomplished based on years of research in this area" (interviews, July 2019). The researcher then showed her some of the responses that she had written 12 years ago. Sue refuted herself quickly. Below is an excerpt from the interview:

> Researcher: Look at this one (showing what she had written in March 2007). You mention that scientific ideas and theories may be considered incorrect even if they were once considered to be true. Look at this one as well (showing what she had written in the post-test in 2007). You believed back then that new evidence can abandon scientific ideas, theories and laws. What made you change your mind over the years?
>
> May: (After reading what she had written 12 years ago) I believe I didn't think as thorough as I had thought when I was in high school (starts laughing)
>
> Researcher: Why not?

May: Life took me to a completely different direction. In high school I was motivated in studying Biology and I loved your classes but then at university I studied something completely different.

Researcher: Do you think your views of the nature of science that you developed in high school were important to you after graduating high school?

May: Not much in my professional life but they were helpful when there was a scientific discussion that I wanted to give my opinion.

Researcher: Can you give me an example?

May: I remember 2 years ago, my friend's mom was taking antidepressants medication. The doctor changed her medication because of side effects that they didn't know earlier. I remembered the discussions we used to have in your class. My friend and her mom kept saying that the doctor is stealing their money. I told them that doctors change their mind based on experiments that they do and they can find new drugs that work better.

4.4.2 Empirical NOS

May's initial view of the empirical aspect of NOS was partially adequate. In fact, she highlighted the importance of evidence in science, yet evidence to her was limited to direct observations. "Scientists know that dinosaurs exist from their remainings that they have found. Their bones are evidence of their existence. These fossilized bones show that they are over 65 million years old… [The scientists are certain about the way they believe dinosaurs look like] because of the bone structures after they have been put together." (Pre-test, 2006).

Throughout her writing, May keeps emphasizing this view. In her second paper, the teacher has placed a side note, encouraging her to reflect on direct and indirect evidence. Her view of the empirical aspect of NOS becomes more adequate at almost the same time when she develops an adequate view of the tentative aspect of NOS. She writes:

> Since science is a changing subject you need evidence. Evidence can come in different ways sometimes like the fossils it is different evidence that make the scientists think hard to come with an explanation. All this helps to have new knowledge. (Reflection paper, March 23, 2007).

The post-test confirms May's adequate view of the empirical aspect of NOS. She highlights the role of indirect evidence in modifying scientific knowledge. She writes:

> Dinosaurs are known to have common ancestors with common reptiles we have nowadays... Maybe, the DNA was analyzed to see what gene existed at that time… They can change their mind based on new evidence. (Post-test, 2007).

In summer 2019, the analysis of May's responses on the post-test shows that she has reverted to her partially adequate view of the empirical aspect of NOS. She writes:

> Fossil remains make scientists believe that dinosaurs really existed… [The scientists are certain about the way they believe dinosaurs look like] because those fossils are enough evidence to draw such conclusions. (Post-test, summer 2019)

During the interview, May clarifies her position further. She mentions that "fossils help the scientists understand the shape and form of the bones and remains of the dinosaurs… Science is like putting the pieces of the puzzle together. Every piece contributes to seeing the big picture more clearly" (Interview, July 2019). Her partially adequate view of the tentative aspect of NOS makes her quite confident that change in science is additive in nature and that evidence contributes only to adding new knowledge rather than modifying or rejecting scientific knowledge.

4.4.3 Subjective NOS

May's view of the subjective aspect of NOS remained almost intact throughout her journey. Initially, her partially adequate view was evident through her responses on the pre-test, where subjectivity in science was primarily related to the experiences of scientists rather than to different theoretical backgrounds that they may have.

> Every scientist probably did their experiment in a different way than the other. This is because some are more experienced than others. Not every scientist comes up with the same experiment and this can cause different results, thus different explanations.

Her views stayed intact throughout the year as reflected through her reflection papers. There is one instance where the teacher has challenged her view of the subjective aspect of NOS and has invited her to think beyond scientists' personal experiences as evident through a side note on a reflection paper that she had written in January 2007.

> Is it possible that different scientists may become influenced by different theories while doing their work? (Reflection paper, January 12, 2007).

May's response on the post-test (2007) shows a similar focus on experience of a scientist contributing to the subjective aspect of science. She writes:

> Science is a subjective subject. Each scientist has his own way of thinking. Scientists analyze the data in different way because of their experience. That is why disagreement can occur.

Twelve years later, May's response is not much different. She claims that "scientists have different experiences, which contribute to different explanations." (Post-test 2019).

Table 1 summarizes each of the four students' 13-year-long developmental journey related to the three aspects of NOS in question.

5 Discussion and Conclusions

The findings of these case studies show that the four students benefited from the NOS intervention in the short term. In general, throughout the course, all four students developed more adequate views of the tentative, empirical, and subjective aspects of NOS compared to their initial pre-intervention views. Right after completing the Honors Biology course, every student had adequate views related to at least two of the three aspects. This shows that the NOS intervention in the Honors Biology course was effective for them in the short term. In addition,

Table 1 The former students' developmental journey

	Sam	Sue	Mike	May
Tentative NOS	IAA	AAA	IPP	IAI
Empirical NOS	PAA	PAP	PAA	PAP
Subjective NOS	AAA	IPI	IAP	PPP

A, adequate; *P*, partially adequate; *I*, inadequate upon the completion of the course, the students had retained their more adequate NOS views that they had developed throughout the year. These findings are aligned with previous studies (e.g., Moss 2001), thus adding another piece of evidence to the existing literature on the notable short-term impact of NOS interventions that use consensus frameworks embedded within explicit and reflective discussions.

This study also shows that the four students' patterns of retaining their NOS views were quite different in the long term. Twelve years after the NOS intervention, Sam was retaining his NOS views, which had become more thorough over the years. Mike was able to retain his views related to two of the three aspects in question. Sue could retain her view related to only one aspect, whereas May could not retain any of her views. It seems that life circumstances, university learning opportunities, and career paths had further shaped the former students' NOS views; however, the gap of data between the years 2007 and 2019 makes it difficult for zooming into the former students' experiences. Yet, these experiences could have led them to deepen, maintain, or revert their NOS views. Carefully designed longitudinal studies are needed in the future that could help better understand how life circumstances, higher education experiences, and career paths shape learners' NOS views.

In fact, Sam was able to develop adequate views of the three aspects of NOS throughout the academic year 2006–2007. He was also able to retain those views 12 years after the intervention. Mike developed adequate views of the empirical and the subjective aspects of NOS as well as a partially adequate view of the tentative aspect of NOS as a result of a year-long intervention. He retained his views of the tentative and empirical aspects; however, his view of the subjective aspect of NOS reverted from an adequate into a partially adequate view. In general, the NOS intervention in the Honors Biology course was mostly effective for these two students in the long term.

Sam and Mike had both pursued science-related majors after graduating from school. It seems that they had the opportunity to engage in further reflections on their NOS views, even though NOS learning was not an explicit component in most of their coursework at university. This finding is aligned with Burgin and Sadler's (2016) report. Additionally, both Sam and Mike had adequate views of the tentative and empirical aspects of NOS, similar to scientists in other contexts as reported by Peters-Burton (2016). These findings complement also those reported by Herman et al. (2013) and Wahbeh and Abd-El-Khalick (2014). In both these studies, participating teachers had retained some of their NOS views. Perhaps science-related careers make possible for former students to continue reflecting on their NOS views and thus retaining them—just like what teachers had done as reported by these two studies. The only reversion was in relation to Mike's view of the subjective aspect of NOS. Although Sam's view was in line with what Bayir et al. (2014) had reported about scientists having informed views about the theory-ladenness in science, Mike's reversion could be attributed to the fact that he pursued a highly technical career, which, according to him, gave no room to think like a scientist.

Sue and May, on the other hand, had their NOS views related to the three aspects reverted over the 12-year period to become similar to those they held before taking the Honors Biology course. Even though each of them had developed adequate views of two of the three NOS aspects at the completion of the Honors Biology course, they could not retain most of their views.

Sue's and May's reversions of NOS views are similar to certain participants' reversions in Akerson et al.'s (2006) and Khishfe's (2015) studies. Additionally, revisiting Khishfe's (2015) postulates described in the introductory section of this paper, although shorter NOS interventions may impede the learners' abilities to retain their NOS views, it does not follow that longer NOS interventions would guarantee retaining of students' NOS views. Sue's and May's reversions of NOS views also question the potential of the Honors Biology course as a more fruitful setting for teaching NOS. High achievement and motivation of Honors Biology students may not necessarily guarantee long-term retention of their NOS views.

Sue's and May's reversions of NOS views also challenge previous findings by Herman and Clough (2016), Herman et al. (2013), Mulvey and Bell (2017), and Wahbeh and Abd-El-Khalick (2014). The NOS intervention in the Honors Biology course was not effective for these two students in the long term. There could be different explanations. First, despite the fact that the Honors Biology course mostly utilized moderately to highly contextualized degrees of science content, the time factor might have contributed to the reversion. Unlike the studies mentioned above, the time elapse between the intervention and the delayed post-test was 12 years.

Second, developmentally speaking, at the time of the intervention, Sue and May were precollege students, unlike the participants in the abovementioned studies who were either pre-service or in-service teachers, and thus at higher developmental positions as Mulvey and Bell (2017) had claimed.

Third, both Sue and May had pursued non-science majors after graduating from school. They also admitted that they never thought about NOS all those years. This is very different from the case of the participants in the abovementioned studies, who were science teachers and thus pursuing science-related careers.

These findings pose several questions regarding *who* benefits from NOS instruction at the school level. Even though it is not possible to derive generalizations from these long-term case studies, and even though the 12-year gap between the post- and delayed post-assessment was only learned about through participant self-reports in one interview, in light of the present findings, the following hypotheses can be suggested:

> *Students enrolled in science-related majors and careers have higher chances of retaining their NOS views gained from school NOS learning experiences than students enrolled in non-science majors and careers* (H1)
>
> *Students enrolled in non-science majors and careers have higher chances of reverting their NOS views gained from school NOS learning experiences than students enrolled in science-related majors and careers* (H2)

Future studies need to test these hypotheses as they can have serious consequences in terms of *who* benefits mostly from school NOS learning experiences. In the long term, a list of questions may arise: Are school NOS experiences more favorable for students who pursue science-related majors and careers? To what extent are school NOS experiences useful for future citizens who do not pursue science-related majors and careers? Considering that NOS is an integral component of scientific literacy, to what extent are school NOS experiences useful for *all* future citizens? How useful is school NOS in preparing scientifically literate future citizens? These and other questions shed the spotlight on issues related to equity and social justice in school science, making one wonder the extent to which school NOS experiences end up providing equitable outcomes for all future citizens.

Findings from this study also reveal that NOS views developed by students are subject to reversion, even if the NOS intervention is intense and contextualized within rich science content. The NOS intervention in this study took place over one academic year and utilized moderately to highly contextualized degrees of science content, yet the developed NOS views did not necessarily retain for a long time.

Finally, this study raises questions related to the long-term impact of the *content* and *methods* (*what* and *how*) used in NOS teaching and learning at the school level. Could consensus frameworks of NOS be responsible for the reversions of NOS views that Sue and May experienced in the long term? Could the responsibility fall on the explicit–reflective approach? Could it be the teacher's fault? Or could it simply be a chance factor that happened with these two students? The data do not suggest any possible directions. Yet, it seems that the long-term impact of school NOS teaching and learning was not high for Sue and May as one would have wished it to be. These results may show that it is not possible to assume that engaging school students in NOS learning using a consensus framework, contextualized within rich science content, and embedded within an explicit–reflective method would necessarily have a long-term impact on students' views of NOS, even if the students were high achievers and highly motivated to learn NOS. The relation may not be a straightforward one as there could be multiple situational factors involved. There is certainly the need for further studies in the form of carefully designed longitudinal studies that can scrutinize this question in more depth. Additionally, there is the need to study the long-term impacts of NOS interventions that use different frameworks of NOS with the purpose of evaluating their relative potentials.

In sum, considering that NOS is important for scientific literacy, the results of this study raise a new set of questions and challenge already-existing assumptions. For example, even if (wishfully) all students graduate grade 12 with adequate NOS views, this may not necessarily mean that their NOS views would be enough for them to be scientifically literate citizens throughout their lives. This can have two implications. First, if the NOS views learned would not last long, then the science education community needs to continue reflecting upon *what* to teach under the title of NOS in school science and *how*. Second, if the NOS views learned would last only for those who choose science-related majors and careers, then *who* benefits from NOS in school science becomes a relevant question that the science education community needs to reflect on. NOS learning should be beneficial for *all* future citizens; otherwise, school NOS would fail to foster equity and social justice.

Compliance with Ethical Standards

Conflict of Interest The author declares no conflict of interest.

References

Abd-El-Khalick, F. (2002). The development of conceptions of the nature of scientific knowledge and knowing in the middle and high school years: a cross-sectional study. Paper presented at the annual meeting of the National Association for Research in Science Teaching, New Orleans, LA.

Abd-El-Khalick, F., & Lederman, N. G. (2000a). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*, 1057–1095. https://doi.org/10.1002/1098-2736(200012)37:103.0.CO;2-C.

Abd-El-Khalick, F., & Lederman, N. G. (2000b). Improving science teachers' conceptions of nature of science: a critical review of the literature. *International Journal of Science Education, 22*(7), 665–701. https://doi.org/10.1080/09500690050044044.

Aduriz-Bravo, A. (2014). Teaching the nature of science with scientific narratives. *Interchange, 45,* 167–184. https://doi.org/10.1007/s10780-015-9229-7.

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*, 194–213. https://doi.org/10.1002/tea.20099.

Akerson, V., Nargund-Joshi, V., Weiland, I., Pongsanon, K., & Avsar, B. (2014). What third-grade students of differing ability levels learn about nature of science after a year of instruction. *International Journal of Science Education, 36*(2), 244–276. https://doi.org/10.1080/09500693.2012.761365.

Akerson, V. L., Erumit, B. A., & Kaynak, N. E. (2019). Teaching nature of science through children's literature: an early childhood preservice teacher study. *International Journal of Science Education, 41*, 2765–2787. https://doi.org/10.1080/09500693.2019.1698785.

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

Allchin, D., Andersen, H. M., & Nielsen, K. (2014). Complementary approaches to teaching nature of science: integrating student inquiry, historical cases, and contemporary cases in classroom practice. *Science Education, 98*, 461–486. https://doi.org/10.1002/sce.21111.

American Association for the Advancement of Science [AAAS]. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

Bayir, E., Cakici, Y., & Ertas, O. (2014). Exploring natural and social scientists' views of nature of science. *International Journal of Science Education, 36*(8), 1286–1312. https://doi.org/10.1080/09500693.2013.860496.

Bell, R. L., Mulvey, B. K., & Maeng, J. L. (2016). Outcomes of nature of science instruction along a context continuum: preservice secondary science teachers' conceptions and instructional intentions. *International Journal of Science Education, 38*, 493–520. https://doi.org/10.1080/09500693.2016.1151960.

Black, K. M. (2006). An examination of preservice teachers' views of the nature of science throughout their science methods course. *International Journal of Learning, 13*(7), 127–134.

Burgin, S. R., & Sadler, T. D. (2016). Learning nature of science concepts through a research apprenticeship program: a comparative study of three approaches. *Journal of Research in Science Teaching, 53*(1), 31–59. https://doi.org/10.1002/tea.21296.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: considerations for effective nature of science instruction. *Science Education, 15*, 463–494.

Clough, M. P. (2007). Teaching the nature of science to secondary and post-secondary students: questions rather than tenets. Pantaneto Press. Retrieved from http://pantaneto.co.uk/teaching-the-nature-of-science-to-secondary-and-post-secondary-students-questions-rather-than-tenets-michael-clough/. Accessed 23 Nov 2020

Cohen, L., Manion, L., & Morrison, K. (2018). *Research methods in education* (8th ed.). NY: Routledge.

Creswell, J. W. (2007). *Qualitative inquiry and research design: choosing among five approaches* (2nd ed.). Thousand Oaks, CA: Sage.

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.

Demirdogen, B., Hanuscin, D. L., Uzuntiryaki-Kondakci, E., & Koseoglu, F. (2016). Development and nature of preservice chemistry teachers' pedagogical content knowledge for nature of science. *Research in Science Education, 46*, 575–612. https://doi.org/10.1007/s11165-015-9472-z.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*. Philadelphia: Open University Press.

Eastwood, J. L., Sadler, T. D., Zeidler, D. L., Lewis, A., Amiri, L., & Applebaum, S. (2012). Contextualizing nature of science instruction in socioscientific issues. *International Journal of Science Education, 34*(15), 2289–2315. https://doi.org/10.1080/09500693.2012.667582.

Erduran, S., & Dagher, Z. (2014). *Reconceptualizing the nature of science for science education: scientific knowledge, practices and other family categories*. Dordrecht: Springer.

Eymur, G. (2019). The influence of the explicit nature of science instruction embedded in the argument-driven inquiry method in chemistry laboratory on high school students' conceptions about nature of science. *Chemical Education Research and Practice, 20*, 17–29. https://doi.org/10.1039/C8RP00135A.

Herman, B. C., & Clough, M. P. (2016). Teachers' longitudinal NOS understanding after having completed a science teacher education program. *International Journal of Science and Mathematics Education, 14*(1), 207–227. https://doi.org/10.1007/s10763-014-9594-1.

Herman, B. C., Clough, M. P., & Olson, J. K. (2013). Teachers' nature of science implementation practices 2–5 years after having completed an intensive science education program. *Science Education, 97*(2), 271–309. https://doi.org/10.1002/sce.21048.

Hodson, D., & Wong, S. L. (2014). From the horse's mouth: why scientists' views are crucial to nature of science understanding. *International Journal of Science Education, 36*(16), 2639–2665. https://doi.org/10.1080/09500693.2014.927936.

Irzik, G., & Nola, R. (2011). A family resemblance approach to the nature of science for science education. *Science & Education, 20*, 591–607. https://doi.org/10.1007/s11191-010-9293-4.

Kampourakis, K. (2019). Science, society, and scientific literacy. *Science & Education, 28*, 603–604. https://doi.org/10.1007/s11191-019-00066-w.

Khishfe, R. (2015). A look into students' retention of acquired nature of science understandings. *International Journal of Science Education, 37*, 1639–1667. https://doi.org/10.1080/09500693.2015.1049241.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551–578. https://doi.org/10.1002/tea.10036.

Kinskey, M. (2020). Elementary preservice teachers' use of speaking, listening, and writing skills to understand the importance of nature of science instruction. *Journal of College Science Teaching, 49*(5), 60–67.

Kolstø, S. D. (2001). Scientific literacy for citizenship: tools for dealing with the science dimension of controversial socioscientific issues. *Science Education, 85*, 291–310. https://doi.org/10.1002/sce.1011.

Kötter, M., & Hammann, M. (2017). Controversy as a blind spot in teaching nature of science. *Science & Education, 26*, 451–482.

Laugksch, R. C. (2000). Scientific literacy: a conceptual overview. *Science Education, 84*, 71–94. https://doi.org/10.1002/(SICI)1098-237X(200001)84:1<71::AID-SCE6>3.0.CO;2-C.

Leblebicioglu, G., Abik, N. M., Capkinoglu, E., Metin, D., Eroglu Dogan, E., Cetin, P. S., & Schwartz, R. (2019). Science camps for introducing nature of scientific inquiry through student inquiries in nature: two applications with retention study. *Research in Science Education, 49*, 1231–1255. https://doi.org/10.1007/s11165-017-9652-0.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: a review of the research. *Journal of Research in Science Teaching, 29*, 331–359. https://doi.org/10.1002/tea.3660290404.

Lederman, N. G. (2004). Syntax of nature of science within inquiry and science instruction. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 301–317). Dordrecht: Kluwer.

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: Lawrence Erlbaum Associates Publishers.

Lederman, N. G., Lederman, J. S., & Antink, A. (2013). Nature of science and scientific inquiry as contexts for the learning of science and achievement of scientific literacy. *International Journal of Education in Mathematics, Science and Technology, 1*(3), 138–147.

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

McComas, W. F. (2017). Understanding how science works: the nature of science as the foundation for science teaching and learning. *School Science Review, 98*(365), 71–76.

McComas, W. F. (2020). Considering a consensus view of nature of science content for school science purposes. In W. F. McComas (Ed.), *Nature of science in science instruction* (pp. 23–34). Switzerland: Springer Nature.

Merriam, S. B. (1998). *Qualitative research and case study applications in education*. San Francisco, CA: Jossey-Bass.

Mesci, G., & Schwartz, R. S. (2016). Changing preservice science teachers' views of nature of science: why some conceptions may be more easily altered than others. *Research in Science Education, 47*(2), 329–351. https://doi.org/10.1007/s11165-015-9503-9.

Miles, M. B., Huberman, A. M., & Saldana, J. (2014). *Qualitative data analysis: a method sourcebook*. Thousand Oaks: Sage.

Moss, D. M. (2001). Examining student conceptions of the nature of science. *International Journal of Science Education, 23*(8), 771–790. https://doi.org/10.1080/09500690010016030.

Mulvey, B. K., & Bell, R. L. (2017). Making learning last: teachers' long-term retention of improved nature of science conceptions and instructional rationales. *International Journal of Science Education, 39*, 62–85. https://doi.org/10.1080/09500693.2016.1267879.

Norris, S. P., & Phillips, L. M. (2003). How literacy in its fundamental sense is central to scientific literacy. *Science Education, 87*, 224–240. https://doi.org/10.1002/sce.10066.

OECD. (2019). PISA 2018 Science Framework. In *PISA 2018 Assessment and Analytical Framework*. Paris: OECD Publishing. https://doi.org/10.1787/f30da688-en.

Peters-Burton, E. (2016). Scientists taking a nature of science course: beliefs and learning outcomes of career switchers. *School Science and Mathematics, 116*(3), 148–163. https://doi.org/10.1111/ssm.12161.

Saldana, J. (2003). *Longitudinal qualitative research: analyzing change through time*. Walnut Creek, CA: Rowman & Littlefield.

Scharmann, L. C., & Butler, W. (2015). The use of journaling to assess student learning and acceptance of evolutionary science. *Journal of College Science Teaching, 45*(1), 16–21.

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: an explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*, 610–645. https://doi.org/10.1002/sce.10128.

Shultz, G. V., & Gere, A. R. (2015). Writing-to-learn the nature of science in the context of the Lewis dot structure model. *Journal of Chemical Education, 92*, 1325–1329. https://doi.org/10.1021/acs.jchemed.5b00064.

Vhurumuku, E. (2010). The impact of explicit instruction on undergraduate students' understanding of the nature of science. *African Journal of Research in Mathematics, Science and Technology Education, 14*(1), 99–111. https://doi.org/10.1080/10288457.2010.10740676.

Wahbeh, N., & Abd-El-Khalick, F. (2014). Revisiting the translation of nature of science understandings into instructional practice: teachers' nature of science pedagogical content knowledge. *International Journal of Science Education, 36*(3), 425–466. https://doi.org/10.1080/09500693.2013.786852.

Yacoubian, H. A. (2015). A framework for guiding future citizens to think critically about nature of science and socioscientific issues. *Canadian Journal of Science, Mathematics and Technology Education, 15*(3), 248–260. https://doi.org/10.1080/14926156.2015.1051671.

Yacoubian, H. A. (2018). Scientific literacy for democratic decision-making. *International Journal of Science Education, 40*(3), 308–327. https://doi.org/10.1080/09500693.2017.1420266.

Yacoubian, H. A., & BouJaoude, S. (2010). The effect of reflective discussions following inquiry-based laboratory activities on students' views of nature of science. *Journal of Research in Science Teaching, 47,* 1229–1252. https://doi.org/10.1002/tea.20380.