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Exploring Chemists' Understandings of the Nature of Science with their Levels of Expertise

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Abstract

Several Nature of Science (NOS) studies have been conducted on different categories of professionals and different age groups. Even though NOS is considered a structural facet of scientific literacy, not much research has been conducted on the NOS ideas of scientists and science professionals. This cross-sectional study investigated the nature of science (NOS) views of 40 participants who have or had exposure to chemistry research using a qualitative comparative analysis approach, in one chemistry department in a large Midwest R-1 university. The participants' chemistry research exposure varied from no research to 31 years of experience. Undergraduates, graduate students, postgraduate researchers, faculty, and scientists were recruited for this study to examine how their NOS understanding develops in relationship to their research exposure. These categories of participants demonstrated different and unique patterns of answers related to aspects of NOS. Science content knowledge and research exposure indeed enhanced science learners'/researchers' NOS understanding, but NOS understanding is not developed in direct proportion to the amount of science content knowledge or research experience that an individual gained. It was observed that professionals with the same expertise level responded to NOS questions similarly, and professionals with different levels of expertise answered NOS questions in significantly different ways.

Introduction

The Nature of Science (NOS) is a critical component of scientific literacy that enhances science learners' understanding and helps them make informed decisions about science and non-science issues (NSTA, 2020). This concept is considered an important educational goal by science education researchers (Allchin, 2020; Lederman et al., 2002; Olson, 2018). While many science educators acknowledge the importance of learning about NOS, it is rare to see effective NOS instruction in science lessons during the early learning stages of science education in the United States (Akerson et al., 2019; Lederman et al., 2002). Several NOS studies have been conducted on different categories of professionals and different age groups, but NOS understanding across the levels of the profession in one field of study is rarely researched. The NOS understanding of scientists (Schwartz & Lederman, 2008), graduate students in science (Aydeniz & Bilican, 2013), undergraduate students (Akerson et al., 2019; Rothman, 2022), and high school chemistry students (Johnston, 2022) have all been studied separately. The

available NOS studies on scientists provide insightful information about NOS understanding among scientists and science professionals (Aydeniz & Bilican, 2013; Pomeroy, 1993; Schwartz & Lederman, 2008; Tira, 2009). However, the conclusions presented in these studies provide only a generalized idea for all scientists; most of them were not specific to their field of expertise.

We believe there may be a correlation between the science professionals' NOS understanding with their field expertise. This dimension of NOS remains a research gap, and more studies are needed to provide conclusions about NOS and how scientists in different fields of expertise interpret it. Different scientists and science researchers have unique field-specific stores of knowledge. In this study, the NOS understandings of scientists and science researchers in the field of chemistry were assessed considering their research expertise. This study investigated how individuals with different levels of research expertise develop NOS understanding. Rather than similarities, this study discusses the dissimilarities of these chemistry professionals across different levels of expertise in the field of chemistry.

So far, the NOS understanding of scientists and Ph.D. candidates has not been studied in connection with their chemistry research expertise. Studying the NOS understanding of chemists in relation to their research expertise would help science educators to understand what factual details these scientists process to understand NOS, and to use and develop chemistry knowledge. Those factual details could be taken and developed to teach NOS to science educators and, ultimately, to science learners. So, the following questions guided this research: What is the relationship between expertise level (Group 1: Faculty, Group 2: Graduate students & Postdocs, Group 3: Undergraduate students) and NOS understanding of chemists, and how do chemists' NOS conceptions change over time and through their experiences?

Theoretical Framework

The theoretical framework in this study is "Epistemology." Epistemology plays a fundamental role in shaping our understanding of the nature of science by addressing questions about the nature of scientific knowledge and the methods used to acquire it (Popper, 1968). According to Popper (1968), scientific knowledge is characterized by its falsifiability and empirical testing, highlighting the importance of rigorous experimentation and critical scrutiny in scientific inquiry. This perspective aligns with the nature of science's emphasis on empirical evidence and the provisional nature of scientific theories (Abd-El-Khalick & Lederman, 2000; Lederman et al., 2002). Moreover, epistemology explores the criteria and standards for evaluating scientific explanations and theories (Kuhn, 1962). Kuhn (1962) introduced the concept of scientific paradigms and revolutions, suggesting that scientific knowledge is shaped by dominant theoretical frameworks and undergoes transformative shifts during periods of scientific revolution. This view contributes to our understanding of how scientific knowledge evolves and changes over time, reflecting the dynamic nature of the scientific enterprise.

Epistemology deals with the nature of knowledge itself, including its origin, scope, and limits. Within the context of NOS, epistemological frameworks explore questions such as how scientific knowledge is acquired, justified, and revised over time. In this study, we analyze our participants' knowledge on NOS against their level of

expertise in Chemistry. While the researchers (us) receive the answers for the NOS questionnaire, our participants actually provide their science knowledge, information, evidence and their own justification on what they already know, not what they do not know. Epistemology provides a foundational framework for analyzing the nature of science by addressing fundamental questions about knowledge, justification, and evidence. By integrating epistemological perspectives, NOS researchers gain a deeper understanding of the principles and processes that underpin scientific inquiry and the construction of scientific knowledge.

Literature Review

Lederman (2008) looked at the Nature of Science as a view of science that blends various aspects of social studies of science, including the historical, philosophical, psychological, and sociological aspects of science. Because science is a socially and culturally embedded entity, it is important to study scientists' understanding of NOS with their demographic factors in mind (Avsar Erumit & Akerson, 2022; Olson, 2018). Previous NOS research has described the understanding of NOS among scientists as 'neither all here nor all there—but everywhere,' meaning that scientists hold different levels of NOS understanding (Schwartz & Lederman, 2008). Some perform extremely well on some tenets of NOS, and other scientists perform relatively poorly on some NOS tenets (Schwartz & Lederman, 2008). Scientists who started studying science education and NOS were able to understand NOS, although they required time to understand and develop an explicit understanding of the NOS elements of their field (McClain et al., 2022; Phillips et al., 2022).

Samarapungavan et al. (2006) provide an effective analysis in the study that they have conducted on chemistry professionals. Though this study did not directly relate to NOS understanding, it provides an effective lesson in the impact of research exposure on the conceptual understanding of science professionals. The Pomeroy (1993) study titled 'Implications of teachers' beliefs about the nature of science: Comparison of the beliefs of scientists, secondary science teachers, and elementary teachers attempted to understand NOS understanding among individuals in different professions. Southerland et al. (2003) studied three scientists' teaching NOS in their college level teaching. There were only three scientists included in this study, which was conducted as a case study. The three scientists had different expertise areas (Chemistry, Physics, and Biology). The Kimball (1967) study was one of the oldest studies conducted on scientists' understanding of NOS, and Kimball examined whether there was any significant difference between scientists and science teachers in their NOS understandings.

It appears that preservice teachers have been studied for their NOS conceptions more than any other category of science professionals. Why do I explore our preservice teachers' NOS teaching practice? The answer is that pre-service teachers (undergraduates) are a group of professionals who teach science to science learners (Akerson et al., 2010; Darling-Hammond & Baratz-Snowden, 2007; Summers et al., 2019). It is hard to teach how to teach (Sadler, 2006), and teaching is a cognitive skill. It was found that pre-service teachers who value spirituality and tradition held inadequate views on the tentativeness of NOS (Akerson & Donnelly, 2008). Another study found that pre-service teachers with inadequate views of tentative NOS tend to be more dualistic (Akerson & Buzzelli, 2007). Even preservice and in-service teachers can find learning and teaching some aspects of NOS more complex than other aspects (Avsar Erumit & Akerson, 2022). Greater background and knowledge of science content did

not necessarily provide more accurate views of NOS (Hanuscin et al., 2006; Scharmann, 1988). Previous studies have shown that an explicit and reflective approach was practical for improving students' conceptions of NOS (Akerson et al., 2019; Bell et al., 2016; Eymur, 2019; Khishfe, 2008; Khishfe & Abd-El-Khalick, 2002).

Schwartz and Lederman (2008) studied scientists' NOS understandings according to their field of study. The researchers stated that the scientists' views were not necessarily consistent with any particular philosophical position, nor did any patterns emerge to suggest a predictable relationship between NOS views and science discipline (Schwartz & Lederman, 2008). The study conducted by Aydeniz and Bilican (2014) can be considered the other most insightful research about the relationship between NOS and scientists. While Schwartz and Lederman (2008) addressed more experienced scientists, Aydeniz and Bilican (2014) focused on novice scientists (science teaching assistants). Aydeniz and Bilican (2014) highlighted that a goal of science graduate education was to help novice scientists to gain and maintain membership in the elite scientific community. Aydeniz and Bilican criticized the novice scientists' (or the science teaching assistants') level of NOS understanding as being not satisfactory, and the researchers assumed that experienced scientists might have a more informed NOS understanding. The studies of Schwartz & Lederman (2008) and Aydeniz and Bilican (2014) were designed similarly.

In summary, a considerable amount of research has been conducted on science professionals' NOS understanding, but few studies have been done on scientists' understanding of NOS, particularly over the course of development through their research experience. In recent studies, researchers have used mixed methods to analyze the data without harming the authenticity of the qualitative data. Most of the studies on scientists' NOS conceptions have been conducted after 2000 and used VNOS-C, VNOS-B, and VNOS-Sci, which are different forms of VNOS (Views of Nature of Science) questionnaires that have been validated by researchers.

Methodology

Due to the exploratory nature of the study, we used a qualitative comparative analysis approach. Participants' written answers on VNOS-C forms, their demographic data, and recorded interview data were analyzed. We could see a very clear correlation between the level of expertise with the NOS understanding, but the existing literature was unable to provide a solid connection as well. This represents one important reason why we chose qualitative comparative analysis for our intra-discipline level of expertise comparison. The intra-disciplinary (chemistry) analysis is well-suited to explore the chemists' views on the Nature of Science along with their research expertise. When compared with the previous studies, this study is different because we analyzed the scientists' understanding of NOS in one particular subject (chemistry) along with their expertise level (research expertise).

Participants

Participants were recruited from the chemistry department of a large R-1 research university in the Midwest. This chemistry department conducts one of the largest undergraduate chemistry programs in the country. An internal electronic invitation was sent to the potential candidates (undergraduate students, graduate students in chemistry,

postdoctoral researchers, and faculty and scientists in chemistry). The invitation link contained a link directing participants to the Qualtrics questionnaire that met their education level. The survey questionnaire was conducted electronically and anonymously.

In the end, we were able to recruit 40 participants for the survey and, out of those participants, we interviewed 12. Although, following the example of Abd-El-Khalick and Lederman (2000), we hoped to recruit 10–20% of the survey participants for the semi-structured interviews, we were able to recruit 30% of the survey participants (12). After analyzing the literature and the nature of this study, the following criteria were set for recruiting study participants:

(1) The participant must be a student (graduate or undergraduate) in the university chemistry program where the study was conducted or in a closely related program.

OR

(2) The participant must have earned a doctoral degree in chemistry (or in a closely related field) and be affiliated with the chemistry department in the university where the study was conducted.

All the participants were divided into three groups (see Table 1). Group 1 contained the people with the highest level of research exposure: research faculty, teaching faculty, and scientists. Group 2 included doctoral students and postdoctoral researchers. Group 3 was composed of undergraduates. We did not recruit any freshmen, focusing instead on seniors and juniors with research experience in chemistry or a related field. However, some juniors and seniors recruited for the study had no research experience due to COVID-19-related restrictions. This study therefore included participants with a wide range of chemistry research experience, from undergraduate students with no research experience to faculty with 31 years of research experience. A comparative study was conducted among these three groups.

Table 1. Participants

Group 1: Faculty (10)	Group 2: Graduates and Postdocs (17)	Group 3: Undergraduates (13)
Research Scientists (S) - 3	Doctoral Students - 13	Sophomores - 1
Teaching Faculty (TF) - 4	Postdoctoral Scholars - 4	Juniors - 6
Research Faculty (RF) - 3		Seniors - 6

Of the 13 undergraduate chemistry students who completed the survey, nine had some research experience. Eighteen graduate and postgraduate participants took the survey. Fourteen were graduate students, all of whom were doctoral students or doctoral candidates in chemistry. They all worked as either teaching assistants or research assistants. In both cases, they worked in a research lab and conducted research with their supervisors. The postgraduates' situation was somewhat similar to the graduate students' situation, although the postgraduates had more independence in their research than the graduate students.

There might be differences in understanding NOS aspects between doctoral graduate students and post-graduate researchers, but, when compared with the other two groups (undergraduates and faculty), graduate students and

post-graduate researchers had sufficiently similar amounts of research experience to be grouped together. Two of the study participants—PG16 (a post-graduate researcher) and G9 (a graduate student)—illustrate this as they both had 10 years of research experience.

Group one included faculty conducting research, who are in the position of greatest authority and play a leading role in research. In general, they are tenured or tenure-track faculty who have the most years of research experience. It also included research scientists affiliated with the university research labs and teaching faculty, who are considered non-tenure track faculty who teach full-time but have no research responsibilities. All these faculty hold a terminal degree in chemistry or a closely related field, and some of them have postdoctoral research experience. All faculty interviewed had more research experience than members of the other two groups.

Data Collection

There are multiple Views of the Nature of Science (VNOS) survey forms available. Due to the participants' backgrounds and the prior research recommendations, we decided to use the VNOS-C survey form to collect NOS related data (Abd-El-Khalick & Lederman, 2000; Lederman et al., 2002). In previous research, VNOS-C was administered to participants with higher cognitive levels and/or higher educational levels, such as college undergraduates and graduates and preservice secondary science teachers and scientists (Abd-El-Khalick et al., 1998; Abd-El-Khalick & Lederman, 2000). Hence, we believed VNOS-C was the most suitable VNOS form for this study.

Participants were recruited from a chemistry department of a large R-1 research university in the Midwest. An internal electronic invitation was sent to the potential candidates (undergraduate, graduate students in chemistry, postdoctoral researchers, faculty and scientists in chemistry). The invitation link contained a link directing participant to the Qualtrics questionnaire that met their education level. The survey questionnaire was conducted electronically and anonymously. Although their preferred contact details were gathered with the expectation of contacting them to possibly participate in the interviews.

Due to the nature of the study, no printed questionnaire was delivered, and no face-to-face interview was conducted. We wanted to recruit more than 24 participants because among the successful modern NOS studies on scientists, that was the highest number of scientists has been recruited for a NOS study (Schwartz & Lederman, 2008). There was no upper threshold number of participants, but we hoped to recruit around fifty participants for the survey. In the end, we were able to recruit 40 participants to the survey and out of those participants, 12 were interviewed. Ten to twenty percent of the survey participants were recommended for the semi-structured interviews (Abd-El-Khalick & Lederman, 2000), but we were able to recruit thirty percent of the survey participants to the interviews.

The sample consisted of 40 chemists and chemistry professionals (13 chemistry major undergraduates, 17 chemistry graduate students and postgraduate scholars, and 10 chemistry faculty) who are affiliated with the chemistry department of a large R-1 level research university in the Midwest. This group has a large variation in

research exposure, high diversity in demographics, and an excellent distribution of research expertise in main chemistry fields (Analytical Chemistry, Inorganic Chemistry, Material Chemistry, Organic Chemistry, Physical Chemistry, and Chemical Biology). Apart from their common subject of study (chemistry), their other demographics are highly diverse.

Table 2. Data Collection Matrix

Research Question	Data Source	Timeline for collection	Data Analysis
Q1: What is the relationship between expertise level and NOS understandings for chemists and how do chemists' NOS conceptions change over time and through their experiences?	Open-ended VNOS-C questionnaire, NSF demographic survey, and semi-structured interviews	After the open-ended VNOS-C questionnaire and demographic survey have been completed.	Data analysis was completed quantitatively and qualitatively. VNOS-C questionnaire data were analyzed qualitatively, and demographics data were analyzed quantitatively.

VNOS-C is an open-ended questionnaire with 10 questions. All 10 items were considered for the main study. However, to identify the significance of the intra field expertise level relative to NOS understanding, answers to VNOS-C Q3 (discusses empirical nature of science), Q4 (discusses tentativeness of science), Q9 (discusses social and cultural embeddedness of science), and Q10 (discusses creativity and imagination of science), where the differences among the expertise level and the NOS understanding is more apparent, were most closely examined.

The National Science Foundation's "Survey of Earned Doctorates" (SED) was used to gather demographic data. Conducted since 1957, the SED is an annual census of all individuals receiving a research doctorate from all accredited U.S. institutions in a given academic year (NSF, 2022). We found the NSF survey to be an insightful survey, and one that is notably up to date. The survey gathers information on the doctoral recipients' (scientists') educational history, demographic characteristics, and postgraduation plans. To make this survey suitable for undergraduate and graduate students, postdocs, and faculty, some questions were slightly modified.

The data collection instrument is a combination of two instruments: VNOS-C and an NSF demographic survey. All participants who completed both surveys were considered for the study. Eligible candidates were continuously reminded and followed up to attend and complete the survey. All participants who completed the survey were invited to the interviews. Those who did not complete the survey were also followed up multiple times to encourage completion. Incomplete surveys were removed from the pool if mandatory information was not completed by the participant. The survey was designed on Qualtrics so that any eligible participant could access it remotely using their university login (login details were not collected). All data related to VNOS-C answers and participants' Chemistry expertise were made mandatory in the survey, so participants were required to answer those before submitting.

Semi-Structured Interviews

The semi-structured interviews were conducted after the surveys had been completed. We aimed to interview ten percent or more of the scientists who have participated in the surveys. We were able to interview 12 participants (thirty percent). The interviews were conducted online using Zoom. The main objective of the interviews was to elucidate and verify the information that participants have provided in their surveys. Abd-El-Khalick (2000) developed an interview protocol to probe participants' views further on relevant NOS issues, and a semi-structured interview form was used for this study. During those interviews, respondents were provided with their questionnaires and asked to explain and justify their responses. Follow-up questions could be used to clarify ambiguities, assess meanings that respondents ascribed to key terms and phrases, and explore respondents' lines of thinking (Lederman et al., 2002). The interview contains possible follow-up questions with the questions in VNOS-C as below.

How are science and art similar? How are they different?

Possible follow-up questions:

- Can you give an example of _____?
- Can you elaborate on _____?

The interviews were conducted to further understand the participants' understanding of NOS and to clarify any discrepancies in the written answers they provided. Among these participants, none of the discrepancies were observed by either researcher. All participants effectively attempted to reinforce the information they provided on the survey by offering additional examples.

Data Analysis

The aim of using an open-ended questionnaire instead of a standardized forced-choice instrument was to gain more insight into the participants' views and to examine the effect of the instruction in this manner. The survey data of VNOS-C are categorized according to Lederman et al.'s (2002) categorization. Each participant is supposed to answer all 10 questions, and each question categorized either as 'naïve' (N), 'informed' (I), or 'adequate' (A) for each question (Abd-El-Khalick & Lederman, 2000; Lederman et al., 2002; Schwartz & Lederman, 2008). If the participant's NOS understanding on the particular question proves to be not consistent with the accepted NOS understanding, then the participant's answer was coded as 'naïve.' If the participant's understanding was consistent with the accepted NOS understanding, then that answer was coded as 'informed.' If the participant's understanding was consistent but they were unable to give further explanation, then the answer was coded as 'adequate.' The analysis was blindly validated by the co-coder (who is the second investigator in this study, and she had many years of research experience in working with NOS. This was extensively discussed in the data analysis section.

The collected data can be categorized according to the scientists' field of study, country of origin, gender, age, and chemistry expertise level. The data analysis was conducted quantitatively and qualitatively. VNOS-C is an instrument to collect authentic qualitative data on NOS from educated adults. Due to that reason, analyzing

VNOS-C data qualitatively and quantitatively needs to be concluded with care. The authenticity of the data should not be erased from the number values that the quantitative data provides.

There were studies in the NOS field that qualitative and quantitative data have been used, and the researchers in those studies have carefully analyzed the data quantitatively and qualitatively without harming the authenticity of the data (Akerson & Donnelly, 2008). Such an approach was followed to analyze the data in this study as well. The participants' answers were coded to identify the common themes using NVivo and used the Abd-El-Khalick & Lederman (2000) analysis guideline to understand the main ideas being presented by participants. Apart from that, the data analysis methods were influenced by the Aydeniz and Bilican (2014), Schwartz & Lederman (2008) and Tira (2009) studies because they were conducted on scientists and graduate students in science. The themes discussed in those studies helped the researchers in this study to understand the main themes and differentiate understandings among the groups. Comparisons were made of responses across the groups to determine where there were differences in NOS conceptions, if any.

Results

All 40 participants answered the VNOS-C questionnaire. We analyzed these results by groups (1, 2, and 3). Substantial trends among the groups were identified among all responses, but the most differing trends across the three groups were visible in their answers to VNOS-C questions 3, 4, 9, and 10, which targeted the validity of observationally based theories and disciplines and the empirical nature of science, the reliable but tentative nature of science, the social and cultural embeddedness of science, and scientific creativity and imagination (Lederman et al, 2002). Hence only those answers are analyzed here and used to draw conclusions.

While giving equal attention to all answers provided by the participants, only informed answers are presented here because they can be analyzed using the VNOS answer guidelines provided by Abd-El-Khalick & Lederman (2000). Although adequate and naive answers can also be analyzed using the VNOS answer guidelines, specific guidelines for analyzing naive answers were not provided. Therefore, these answers were not explicitly analyzed due to a lack of guidelines and analysis methods.

Empirical Nature of Science (Q3)

Group 1: Ten faculty and scientists participated in this study, and they held an average of 17 years of research experience. Eight participants of Group 1 (faculty and scientists) had informed understandings of the empirical nature of science, while two had adequate views. The following is an informed answer provided by a teaching faculty on VNOS-C Q3 (empirical nature). VNOS-C Q3 mainly discusses the NOS aspect of validity of observationally based theories and disciplines and the empirical nature. In Lederman et al., (2000), a guide has been provided to assess an informed answer and naive answer (p.515). All these answers were assessed according to the said guidelines.

“No. For traditional development of scientific knowledge, you must isolate a variable and test that while

controlling the rest of the variables.....For example, penicillin was discovered by accident and there was not an experiment designed to try and create it.....not all scientific knowledge we have gained REQUIRES experiments.” (TF10)

TF10 said ‘No’ to the first question, but then explained that an experiment is not the only way to generate an answer—there are many other ways to generate scientific knowledge. Even though TF10 said no to the first question, this answer was categorized as ‘Yes and No’ because of the perspective the elaborated answer displayed. TF10 did not say that experiments are unimportant; TF10 said that experiments are one of the most important among many methods—even scientists invent important things by accident.

The majority of faculty and scientists (80%) agreed that experiments are required for the development of science. Those answers were categorized into the ‘Yes’ subgroup. Some of them said that yes, experiments are required for the development of scientific knowledge, but that observations and accidents in experiments help to develop scientific knowledge as well. Such answers were categorized into the ‘Yes and No’ subgroup. No faculty or scientists stated that experiments are not needed for the development of scientific knowledge, an answer which would have been coded ‘No’.

Including TF10, seventy percent of the faculty and scientist participants provided informed answers to this question to VNOS-C Q3 (empirical nature). TF10 explained how Penicillin was invented by accident to provide a counterargument. Another provided an analogy from cake baking to describe learning from trial and error. Yet another participant described isolating the cause of COVID-19 from other effects. The invention of Penicillin was related to chemistry and biochemistry. COVID-19 causes may also be traced to chemistry to some extent. The cake-baking example is not related to chemistry. The following is an informed answer for the experimental NOS provided by a teaching faculty member.

Scientific theories can change.....an experiment may come along that disproves some fundamental aspect of a theory. Experimental techniques are constantly evolving..... Consider how atomic theory evolved..... However, we should learn theories to give ourselves a starting point for exploration (TF4).

Group 2: 17 participants administered to this study from Group 2. For both postdocs and grad students, conducting research is a high priority, and those in this study held an average of 7.5 years of research experience. Eight Group 2 participants (out of 17) provided informed answers to VNOS-C Q3 (empirical nature) Graduate and postgraduate students responded to the question about empirical NOS (Q3) somewhat similarly to faculty and scientists. They affirmed that science needs experiments, which differentiates science from non-science subjects. They further mentioned that many early philosophical assumptions were later disproved by scientists through experimentation. Three of the graduate/postgraduate participants acknowledged the importance of experiments while also maintaining that it is highly subject-related. Subjects like chemistry and biology require experiments, while other subjects generate knowledge from observation. Participants also stated that new knowledge can be generated from the literature. Such answers were sub-coded to ‘Yes and No.’ Only one participant stated that experiments are not needed. That participant said that without knowledge, experiments cannot be conducted—an answer that was sub-

coded as 'No.' Graduate student G7's answer to VNOS-C Q3 (empirical nature) is representative of "yes" answers provided by Group 2:

Yes. Even theoreticians using math and computers to investigate unexplored phenomena are creating an experiment of sorts (changing a parameter in the simulation etc.). One could argue that a mere observation is not an experiment and can lead to knowledge, such as looking through a telescope to identify stars/planets/etc. However, to truly understand those observations, they must be observed over time (where time is the perturbing parameter) These would qualify as experiments in order to understand the observable nature (G7).

Group 3: 13 undergraduates participated in this study (1 - sophomore, 6 - junior, and 6 - senior). They hold 0.8 years of research experience in average while four of them did not have any research experience at all. Undergraduates' answers to the VNOS-C questions displayed different patterns than both Groups 1 and 2. Seven undergraduate students have provided informed answers while five of undergraduates provided adequate views on empirical nature of science. Undergraduates have an advantage when answering VNOS questions because their sources are not limited to chemistry and science but include their understanding of multiple fields. Undergraduates' understandings of the empirical NOS differed somewhat from those of faculty and graduate-postgraduate researchers. Undergraduate students leaned towards the 'Yes' side rather than 'Yes and No.' Undergraduates presented their answers with numerous insightful examples justifying the importance of experiments to the development of science. They appeared to recognize experiments as the base of scientific knowledge: without experiments, science is just a set of predictions. It is interesting that participants who were highly involved with research and experiments provided answers to this question ranging from 'experiments are important' to 'experiments are one way of knowing and generating scientific knowledge,' while, conversely, undergraduate students with little or no research exposure strongly agreed that experiments are the most important way of generating scientific knowledge. For example, this response was provided by U12.

Yes. Without experiments, we would have no way to collect real, quantitative data about our observations. We develop our knowledge based on what we see in experiments. This isn't to say that experiments are where science stops - we still need to analyze our data and muse about why we saw what we saw - but that data is how we can come up with ideas about how the world works. If we just made-up predictions and never tested anything, then someone could predict that oil and water will mix just fine and present a theory with no evidence to back it up. Experiments provide the much-needed meat that makes up the basis of our scientific theories (U12).

Tentative Nature of Science (Q4)

Group 1: Eight faculty participants provided informed answers to indicate their understandings of the tentative NOS to VNOS-C Q4 (tentativeness). They said that theories change (often), or that theories are constantly evolving—which according to them is a much broader and more appropriate term. It seems the faculty acknowledge new evidence they gain from their experiments or from any other scientific methods and that they

are flexible in changing their theories accordingly. When technology advances, instrumentation advances too. This allows scientists to explore smaller or much larger objects and substances. This ongoing exploration and flexibility to change allows scientists to draw informed conclusions about their understanding of science.

Group 2: Fourteen graduate and postgraduate researchers provided informed answers to questions about the tentative NOS. They mentioned that scientists may come up with new theories that replace the existing theories, because the new theories have the full support of experimental data. They explained that, with the development of scientific instrumentation and the advancement of technology, repeating the same experiment could possibly yield different and more accurate data.

Most of the graduate and post-graduate researchers conveyed similar ideas. These researchers in the chemistry department are involved in full-time or part-time research, so these answers resonate with the work they are currently conducting. The following is a response to VNOS-C Q4 (tentativeness) provided by G4, a graduate student in chemistry with nine years of research experience in chemical biology:

Theories are always changing, that is why they are theories. Science is designed to test and hone our knowledge of a subject.....We learn the current day theories because they provide the groundwork for what we already know. Current theories serve as the framework for the design and testing of new theories. Even if they are ultimately incorrect, at least they are a starting point, so we don't just rediscover the same things over and over again (G4).

Group 3: A junior chemistry major without any research experience, U5, provided this informed answer about the tentative NOS. U5 expects to pursue employment in industry.

Yes, scientific theories can change over time. Science isn't quite set in stone, back in the 1800's Lord Kelvin thought all of physics was solved except for like 2 things. Turns out, he was wrong and Einstein and a whole bunch of other physicists proved him wrong on that front. Another example was our understanding of classical mechanics, this didn't hold up at the atomic and subatomic levels, so science ran experiments and tested hypotheses to discover quantum mechanics and string theory (with much more theories as well, crazy stuff happening down at the subatomic level lol). Theories change, however, because our understanding changes over time. In summary, theories can change over time as new testing and results are done. For part b, it's no different than learning to walk. Sure, there is running which would be a quicker way to get around campus, but sometimes we need to learn about something to figure out if there's a better way to do said thing. Whether or not theories hold up is just science being conducted (U5).

Fifty-four percent of the undergraduate participants provided informed answers regarding the tentative NOS. When compared with the other two groups (faculty and grad-postgrad researchers), they provided fewer informed answers. However, all the rest of the participants in Group 3 (46%) gave adequate (mixed) answers. The undergraduates' answers were somewhat similar to the faculty and grad-postgrad researchers answers, but

undergraduate answers tended to provide more information originating outside chemistry textbooks. They mentioned classical physics, quantum physics, and germ theory, to name a few. Specifically, many undergraduates described Einstein and the recent attempt to disprove Einstein's theory of relativity as an excellent example of the tentativeness of science. One faculty member and one graduate student described Newtonian physics and Quantum physics in their answers to Q4, but they were the only ones in their groups to do so.

Social and Cultural Embeddedness of Science (Q9)

Group 1: Regarding social and cultural embeddedness of science, we noticed substantial differences in conceptions across expertise level. Seven out of 10 faculty and scientists (70%) provided informed answers. All discussed the external influences on science and scientists or the self-biases of the scientists. The scientists and faculty further said that their research was heavily dependent on funds from external sources, including the government. Even though science is universal, the funding sources decide where scientific research should be guided. Hence science is socially and culturally embedded. One faculty member described the science and technology practiced in indigenous people in New Zealand, and another provided an example from the COVID-19 pandemic and explained how it would affect the path of the science and research for many years. The following answer was provided by S5, a research scientist in Chemistry.

In science, the questions one asks, that is the data one chooses to measure or to include, have profound impacts on what conclusions can be drawn..... Experiments made using different techniques gave higher values but many authors still reported values closer to Millikan's.....Confirmation bias is a strong human trait that must be fought by scientists of all stripes.....now know that the effect of medications on certain conditions can be quite different between men and women or western Europeans and east-Asians. Science is universal, the observer is still human (S5).

S5 gathered information to confirm their idea and presented strong evidence that science is universal but recognized that the observer and the scientist are still human. Therefore, the course of science is socially and culturally embedded. S5 provided two examples: one from chemistry related to Millikan's oil drop experiment and the other from medicine. From both these experiments, S5 attempted to explain that the course of science is guided by humans who are highly socially and culturally embedded.

Group 2: Ten graduate and postgraduate participants shared informed responses about the social and cultural embeddedness of science, and their opinions about science varied: science is universal, science should be universal, and science is not universal. In all cases, they agreed that science is socially and culturally embedded because of people's influence. They drew examples from the COVID-19 pandemic and vaccine, medical studies on Caucasian people, the space race, the HIV/AIDS epidemic, and homosexuality to support their opinions on the social and cultural embeddedness of science (Ariyaratne, 2023). The following response was provided by a graduate student with an undergraduate degree in chemistry and one year of research experience.

Fundamentally, science is universal..... However, science is not always interpreted and used in a

universal way, which is an impact of individuals social and cultural values. Vaccination is one controversial topic that is based in science. There is a lot of data on vaccines, most says they're helpful in treating disease, and some says there can be complications....While this decision is not well-informed, it is a product of genuine scientific experimentation, though often twisted by individual values (G5).

This informed answer describes how the social, cultural, and political opinions of the governing bodies try to manipulate information or the definitions for their own benefit or because of their moral values. Ten graduate and postgraduate participants answered this question, and their opinions about science varied: science is universal, science should be universal, and science is not universal. In all cases, they agreed that science is socially and culturally embedded because of people's influence. They drew examples from the COVID-19 pandemic and vaccine, medical studies on Caucasian people, the space race, the HIV/AIDS epidemic, and homosexuality to support their opinions on the social and cultural embeddedness of science (Ariyaratne, 2023).

Group 3: There were six undergraduate participants who provided informed answers regarding social and cultural embeddedness, citing examples such as military devices, germ theory, the Kinsey Institute (an internal institute for research in sex, gender, and reproduction), and homosexuality and bisexuality-related topics to prove the idea that science is socially and culturally embedded. The following informed answer about the social and cultural embeddedness of science was provided by U8, a junior in biochemistry with one semester of research experience:

I think that science itself is universal, but I think applications of science are definitely often infused with people's social and cultural beliefs. One example is the recent abortion controversy in the US. The political climate in the US Supreme Court, for the majority of them, overlooked the basic science around the development of a fetus, and chose what defines a "life" or child based on their personal political agendas. I think everybody does so with this subject to an extent, regardless of their view, because the science of pregnancy can be interpreted in different ways to fit different agendas (U8).

U8 picked a highly controversial topic to explain and defend the idea that science is socially and culturally embedded. U8 used abortion and the definition of human life, arguing that lawmakers are trying to define "life" and "fetus" to cater to their moral and religious values. That can be considered as social-cultural embeddedness. It was noted that three undergraduate participants described issues related to the current abortion laws in order to prove the social and cultural embeddedness of science. One participant provided detailed information about sexual orientation and the popular 80s definitions of same-sex interactions to prove that science is socially and culturally embedded. No faculty or graduate-postgraduate participants provided any information related to abortion or sexual orientation. It seems that undergraduates selected information from the current world to critique current issues. Such attempts were not visible among faculty and graduate-postgraduate researchers in this study. Instead, researchers and scientists brought evidence and examples from traditional science topics.

Imaginative and Creative Nature of Science (Q10)

Group 1: Nine faculty and scientist participants provided informed answers to this question, meaning that all but

one of the Group 1 members provided informed answers. (The exception provided an adequate answer.) All participants in this group agreed that the design stage of an experiment requires the most creativity and imagination. Also, most of them agreed that scientists need to be creative in the data analysis part as well. Some said that scientists need to be creative in all stages of research, but others said that data collection does not require much creativity. However, all agreed that scientists need to be creative, and that their scientific work should be creative as well. In response to VNOS-C Q10 (which discusses creativity and imagination of science), scientist S9 provided this answer:

Yes, scientists do need their imagination and creativity. For one, they use them at planning and design stage because they have to expect something from the experiments. And for two, they use their imagination and creativity at data analysis stage because they should think about why certain results happen..... They should be creative because they can look from different angles which might help the advance of science (S9).

This scientist strongly agreed that scientists need imagination and creativity. S9 described two different stages in research in which scientists use imagination and creativity: in the planning and designing stage and in data analysis. It seems like S9 made an effort to say scientists use creativity and imagination in all stages of scientific research. We interpret S9's statement to mean that scientists should be creative because creativity allows them to look from different angles, identifying different possibilities and different answers. S9 is a research scientist in material chemistry who, interestingly, learned about NOS from the undergraduate supervisor.

Not many examples were provided by the participants to justify their answers. One participant said that scientists need creativity and imagination to avoid "tunnel vision," or looking merely for the results they want. One participant provided an example from Einstein's exploration of the photoelectric effect:

Yes, scientists are creative at all stages of the process. Planning a novel experiment often takes a leap of insight (e.g. Einstein thinks the wavelength of light is more important than the intensity when electrons are ejected from illuminated surfaces). The data collection apparatus itself often requires great creativity to conceive of as often the apparatus may never have been built before. Take the magnetic sector mass spectrometer. Putting an electrostatic filter on it (as Aston did) to control the energy of the ions greatly improved the resolution and allowed the isotopes of neon to be clearly observed in 1919. Finally, data analysis can require extreme creativity as one must select which variables to compare and how best to test the significance of any result/prediction (S5).

S5, a scientist, tended to provide more elaborate answers with examples. It seems this mass spectrometer example might be related to S5's own research experience. During the follow-up interview, S5 provided examples with mass spectroscopy and said that S5 worked with the most sophisticated mass spectrometers in the university.

Group 2: Eleven participants provided informed answers to questions about the creative and imaginative NOS. They all agreed that scientists need creativity and imagination for their science experiments and investigations.

Some said that scientists require creativity and imagination for all stages of their experiments. Most maintained that scientists need creativity and imagination skills in the planning and designing of the experiments, as well as for data analysis. Most of the participants also indicated a high degree of certainty about the use of creativity and imagination in the scientists' work. This conviction is reflected in language such as, "Yes, absolutely," and, "I believe that scientists are very creative." For example, G1 provided this answer in response:

Yes, absolutely. There is no science without creativity and imagination. I think this is true at all stages. It takes creativity and imagination to develop a hypothesis where there was once nothing. Even if based on previous trends, a hypothesis is an original, testable thought.....I realize not all science is an adventure. Some of it can be very mundane (sometimes necessarily so); in those cases, maybe creativity and imagination are not critical. But I think if you have those qualities, you can go much deeper into discovery than otherwise (G1).

This answer reflects strong agreement with the creative and imaginative aspects of NOS and in all stages of scientific experiments/investigations. G1 was a graduate student in inorganic chemistry with seven years of research experience. G1 completed an undergraduate degree in chemistry and as well as in ancient Greek and Latin.

Because this study was conducted at an R-1 level research university, the graduate and post-graduates surveyed were all highly engaged with research activities. It appeared to be these participants (graduate and postgraduate researchers) answering this question from their own research experience. That might be the reason we did not see any external examples provided by the graduate and post-graduate researchers in the informed answer section.

Group 3: Nine undergraduates have provided informed answers to creativity and imagination of NOS. This informed conception of creativity and imaginative NOS was provided by U5, a junior chemistry major who learned about NOS through a science class:

I would probably say yes. Creativity and imagination are ways to think outside the box on issues that we face. So, in theory, we as scientists would think about how different things in the universe operate and that takes some creativity to imagine things such as how a new drug is going to theoretically act inside a human body. Or how a gas cloud in the cosmos is going to behave next to a neutron star. There are things that we can't quite test as readily as we'd like, so thought experiments come in real handy from time to time. I would say that most, if not all, science is using creativity and imagination in the planning and design phase of the scientific method, but not so much during the data collection and analysis phase because those things need to follow a certain order/way of being done to be done correctly (U5).

This undergraduate agreed that scientists need creativity and imagination skills for scientific investigations. Interestingly, the undergraduates who gave informed answers seemed less certain than faculty-scientists and graduate-postgraduate researchers who also answered in an informed way. Consider U5's words: "I would probably say yes." Other undergraduates who answered in an informed way started with phrases like "I believe"

or “I think scientists use imagination and creativity.” This stands out in comparison to the faculty, scientists, and graduate post-graduate researchers who were extremely certain about the use of creativity and imagination.

All undergraduate participants who gave informed answers agreed that scientists need creativity and imagination during least at one stage of their experiments and investigations. Many said that scientists use creativity and imagination at all stages of the process. Some said that scientists use creativity and imagination the most during the planning and designing stage and the data analyzing stage. However, faculty, scientists, graduate students, and postgraduate researchers were extremely certain about the use of creativity and imagination. That might be because they are either currently researchers and scientists or have been researchers at some stage of their lives. These Group 3 participants were less certain than those from Groups 1 and 2, perhaps because they lacked research experience.

Discussion

We conducted this study to identify how experience with chemistry research impacts the development of NOS. As such, we categorized the study participants into three groups according to their research experience. Group 1 (faculty and scientists) had an average research experience of 17.5 years. Group 2 (graduate students and candidates in chemistry department and postgraduate researchers) had an average of 7.5 years of research experience. Group 3 (junior and senior chemistry undergraduates) had an average of 0.8 years of research experience. These three groups' data were collected and studied separately to understand any trends in their survey and interview answers. As it was mentioned previously, there is a relationship between the years of research experience that a participant has and their understanding of the NOS. However, the number of years that an individual participated in research was not the only factor that affected their understanding of the NOS. These three groups understood the NOS in exceptionally different ways, not only because of differences in their research exposure, but also because of differences in the nature of their research, the responsibilities they hold in the research process, and their connections with science and non-science community and society.

None of the groups performed better in all NOS aspects. Group one (faculty and scientists) performed well in most of the NOS aspects (such tentativeness, and empirical nature aspects of NOS) when compared with the groups two and three, but they performed no better than other groups in a few of the NOS aspects, for example subjectivity aspect of NOS and observation and inference aspect of NOS were poorly performed by faculty when compared with the other participants. In some areas, all groups performed well such as the social and cultural aspect of NOS and creativity and imagination aspect of NOS, and, in other areas, all group participants performed poorly such as Q5 theory and law aspect of NOS (not discussed here). Furthermore, the parities in between groups for each NOS aspect were analyzed individually with the answers each participant provided. The participant groups were analyzed according to the following NOS aspects.

Faculty and Scientists

These participants had the greatest number of years of research experience. Their NOS understanding was well-

developed. They displayed an excellent comprehension of the survey questions and answered the questions as instructed. They avoided personal bias in their answers. Usually, they explained their examples well. Perhaps because they teach and research the subject (chemistry), they provided a lot of examples and analogies relevant to chemistry, including VESPR Theory, Beer-Lambert law, and the evolution of atomic model theory—which are highly related to the field of chemistry. When they did not have an example from chemistry, they offered examples from other sciences, such as physics and biology. When they failed to find a science-related example, they used examples from day-to-day life such as baking, cooking, etc.

They were extremely reluctant to mention socio-political concerns. No faculty discussed anything related to culture, politics, and social issues. It seems the faculty tried to avoid bringing such topics to the discussion, which they may also practice in their teaching. In general, chemistry (and many other natural sciences) does not appear to be connected to social issues. Hence faculty seemed to purposely stay away from discussing social issues, even though VNOS-C makes plenty of space to discuss science and society. Their responses were directly focused on science examples, and not social aspects connected to science.

Graduate Students and Postgraduate Researchers

The graduate students also provided many chemistry examples, as well as examples from other science subjects, like physics and biology. One graduate student mentioned the role of imagination in developing the Kekule structure of Benzene (Ariyaratne, 2023). Many of the graduate student participants mentioned Newton's Laws of Motion and Einstein's theory of special relativity and general relativity. However, like group one participants, their explanations were not precisely clear. Group two (graduates and postgraduate researchers) mostly took examples from science and sometimes non-science disciplines. However, unlike the faculty group, they provided explanations from non-science fields when necessary. Group 2 participants discussed topics such as COVID-19 vaccination choices and the HIV/AIDS epidemic.

However, unlike the faculty and undergraduate groups, Group 2 participants (graduate students and postgrads) exhibited a hierarchical value of science over other subject disciplines. With the exception of only a few participants, most of Group 2 did not believe that any other discipline (such as philosophy and religion) could explain the world. That means that they considered chemistry and other natural sciences to be superior to some other subjects. Even though they did not say it exactly, they mentioned chemistry and other hard sciences are more "refined" and "explored" than other non-science subject disciplines. Unlike faculty and undergraduates, this group (graduate students and postgrads) studied only one subject (chemistry) for a very long time, which might be a reason they developed such a belief.

Undergraduates

Group 1 participants (undergraduates) had the least amount of research experience. They did not often mention chemistry examples in their VNOS-C answers, but they did provide examples and analogies from other science subjects. This group, unlike the other two groups, mentioned many current science-related issues, social and

cultural phenomena, etc. Their understanding of the NOS was informed by modern technology and new inventions of science. Sometimes their sources of information were too informal. They offered examples including quantum mechanics, the special theory of relativity, and references to particles that can move faster than the speed of light. These acknowledgments of science topics by the undergraduate does not mean that they are experts in many fields; undergraduates are aware of many fields and their intellectual level is better than many in society. However, when compared with the faculty, grad students, and postdocs, their knowledge in science would be a “mile wide but an inch deep”.

However, undergraduates seemed tremendously aware of current affairs, and they demonstrated an openness to critique and bring analogies from the day-to-day world, politics, culture, and society. They brought a range of topics to the discussion, including abortion rights, LGBTQIA+ rights, and the definition of life in the womb—all of which were highly debated topics in society during the time this data was collected. These undergraduates showed a great example of understanding the world with the skills and knowledge that they gathered from science. However, their responses did not indicate that they had as high science content knowledge as the scientists who were studied.

Conclusion

Previous studies have examined the researcher’s mode of study (experimentally based, observational or theoretical) alongside their NOS understanding. The three groups we studied—undergraduates; graduate students and postgraduate researchers; and faculty—had distinct research profiles, ranging from no research to 31 years of research expertise. This allowed us to study the relationship between research experience and NOS understanding extensively. These three groups performed differently in different NOS aspects. The differences between groups were significant and clear in VNOS-C Q3 (empirical nature), Q4 (tentativeness), Q9 (social and cultural embeddedness), and Q10 (creativity and imagination).

The faculty and scientists of Group 1 performed better than both other groups in many NOS aspects. Even though the faculty addressed some aspects of NOS poorly such as observation and inferences of NOS aspect and subjectivity aspect of NOS, overall, the most informed answers were provided by Group 1. Their answers and explanations were refined.

Group 2 (graduate and postgraduate researchers) demonstrated significant differences in their understanding of the NOS compared to Group 1 and Group 3 participants. The responses of Group 2 reflected a greater scope than the faculty participants’ answers. Group 2 participants discussed chemistry-related topics, science topics, and non-science topics, but they tended to give chemistry and science knowledge a higher value than the other non-science knowledge. We did not see this significant trend among Group 1 and 3 participants.

It is difficult to say that faculty and scientists perform well and that they are more informed in NOS aspects than undergraduates, or vice versa. Except for a few NOS aspects, Group 1 faculty and scientists performed better than all other participants. That said, we are not ready to say that research experience correlates to NOS understanding,

because, for a few NOS aspects, Group 2 participants performed most poorly of all the groups. This was unexpected, because Group 2 had more research experience than undergraduates. This revealed that the number of years of research experience (the quantity) is not the only factor in developing an understanding of NOS; the quality (or the role) of the research conducted is significant as well.

Limitations of the Study

The sample size is considered significantly large when compared with the previous studies (Aydeniz & Bilican, 2014; Schwartz & Lederman, 2008). However, when studying the individuals, it was apparent that there are differences inside the groups due to many different variabilities in the ideas expressed by individuals. To reduce such intra group variability, the researcher tried to relate the questions to their field of expertise (Chemistry). As the number of years of someone's chemistry research exposure changes, so do their age, profession, education, marital status, social status, etc. These external factors influence individuals' understanding of science and the world and could impact their NOS understanding as well. Such factors would likely change parallel to an individual's years of research expertise.

Recommendations for Future Research

This study was conducted in a chemistry department at an R-1 level, large research university in the Midwest. This chemistry department holds one of the largest graduate and undergraduate chemistry programs in the country, and both programs are top ranked in the United States. Both programs are diverse, as they recruit local and international students. Diversity among the faculty and the researchers is also high. Hence, we were able to recruit many international and local participants to the survey. Even though there is high diversity among the faculty and the students, our group of participants can still be considered as a selected pool in chemistry. As this is an R-1 high-research university, the students in these programs are highly qualified, and the faculty and scientists are exceptionally qualified and experienced. As such, this pool of participants may not accurately represent all chemistry professionals and learners in the United States.

When comparing the three groups, it appeared that there were three different understandings of science and chemistry among them. Group 1, comprised of faculty and scientists, explains NOS (Nature of Science) using science itself. Faith also has a considerable impact on their NOS beliefs. Additionally, they utilize day-to-day analogies, such as those from baking and cooking, to explain science. In contrast, undergraduates learn about NOS through the lens of science and society. They attempt to explain social and cultural issues using scientific principles, citing examples like abortion rights, gay marriages, the HIV/AIDS epidemic, and vaccine mandates. When educating undergraduates, chemistry educators should understand that they not only have to teach chemistry but also need to explain worldly and societal issues using chemistry.

Group two (graduate and postgraduate researchers) did not seem to incorporate any external, non-science-related information to question or inquire about science. The majority stated that they did not use any non-science information to explain NOS aspects. Their understanding of science was vastly subject-focused, and it seems they

believed that science is the only way of 'knowing things.' Consequently, they attempted to hierarchically value scientific subjects over others, as indicated throughout their survey responses and interviews. Graduate students and postgraduate researchers have studied science formally for many years and have conducted research in one particular aspect for several years. Such circumstances might lead them to become strong believers in science. However, undermining other ways of learning about the world could adversely affect them. Therefore, research supervisors and scientists should encourage graduate students and postdoctoral researchers to explore other fields and motivate them to stay updated with current events.

A large percentage of scientists and graduate students in STEM in the United States are foreign-born individuals. Some of our study participants were not native English speakers, and some of them had only lived in an English-speaking country for one year. Their chemistry knowledge was excellent, but they were not fluent in English and struggled to answer the NOS questionnaire in English. We also observed that most international participants of this study had a hard time elaborating their ideas during the follow-up interview. Therefore, unless they were asked extra questions, they tended to repeat the same answer they provided on the survey.

After analyzing all the research findings from this study and the literature from the previous studies on scientists and science learners, it can be concluded that science content knowledge develops science learners' NOS understanding. However, NOS understanding is not developed proportionally to the amount of science content knowledge developed. NOS understanding is developed according to the way an individual logically questions, compares, and contrasts science knowledge with non-science knowledge, society, and the world.

Ethics Statement

This research was reviewed and approved by the Institutional Review Board of Indiana University – Bloomington, USA (#17344).

Reference

- Abd-El-Khalick, F., & Lederman, N. G. (2000). 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>
- Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education*, 82(4), 417–436. [https://doi.org/10.1002/\(sici\)1098-237x\(199807\)82:4<417::aid-sce1>3.0.co;2-e](https://doi.org/10.1002/(sici)1098-237x(199807)82:4<417::aid-sce1>3.0.co;2-e)
- Akerson, V. L., & Buzzelli, C. A. (2007). Relationships of preservice early childhood teachers' cultural values, ethical and cognitive developmental levels, and views of nature of science. *Journal of Elementary Science Education*, 19(1), 15–24. <https://doi.org/10.1007/bf03173651>
- Akerson, V. L., & Donnelly, L. A. (2008). Relationships among learner characteristics and preservice elementary teachers' views of nature of science. *Journal of Elementary Science Education*, 20(1), 45–58. <https://doi.org/10.1007/bf03174702>

- Akerson, V. L., Buzzelli, C. A., & Donnelly, L. A. (2009). On the nature of teaching nature of science: Preservice early childhood teachers' instruction in preschool and elementary settings. *Journal of Research in Science Teaching*, 47(2), 213–233. <https://doi.org/10.1002/tea.20323>
- Akerson, V. L., Carter, I., Pongsanon, K., & Nargund-Joshi, V. (2019). Teaching and learning nature of science in elementary classrooms. *Science & Education*, 28(3–5), 391–411. <https://doi.org/10.1007/s11191-019-00045-1>
- Allchin, D. (2020). Historical inquiry cases for teaching nature of science analytical skills. *Science: Philosophy, History and Education*, 595–607. https://doi.org/10.1007/978-3-030-57239-6_32
- Ariyaratne, T. (2023). (thesis). *Comparing chemists' views of the nature of science (NOS) with their levels of research expertise*. Indiana University ; ProQuest Dissertations Publishing, Bloomington, IN.
- Avsar Erumit, B., & Akerson, V. L. (2021). Using children's literature in the Middle School Science class to teach nature of science. *Science & Education*, 31(3), 713–737. <https://doi.org/10.1007/s11191-021-00274-3>
- Aydeniz, M., & Bilican, K. (2013). What do scientists know about the nature of science? A case study of novice scientists' views of nos. *International Journal of Science and Mathematics Education*, 12(5), 1083–1115. <https://doi.org/10.1007/s10763-013-9449-1>
- 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(3), 493–520. <https://doi.org/10.1080/09500693.2016.1151960>
- Darling-Hammond, L., & Baratz-Snowden, J. (2005a). A good teacher in every classroom: Preparing the highly qualified teachers our children deserve. In *Educational Horizons* (2nd ed., Vol. 85, pp. 111–132). essay, Jossey-Bass.
- Darling-Hammond, L., & Baratz-Snowden, J. (2005b). *A good teacher in every classroom: Preparing the highly qualified teachers our children deserve* (Vol. 85). Educational Horizons.
- Eymur, G. (2019). The influence of the explicit nature of science instruction embedded in the argument-driven inquiry method in chemistry laboratories on high school students' conceptions about the nature of science. *Chemistry Education Research and Practice*, 20(1), 17–29. <https://doi.org/10.1039/c8rp00135a>
- Hanuscin, D. L., Akerson, V. L., & Phillipson-Mower, T. (2006). Integrating nature of science instruction into a physical science content course for Preservice Elementary Teachers: Nos Views of teaching assistants. *Science Education*, 90(5), 912–935. <https://doi.org/10.1002/sce.20149>
- Johnston, M. (2022). Nature of Science in an NGSS Chemistry Classroom. In V. Akerson & I. Carter (Eds.), *Teaching Nature of Science Across Contexts and Grade Levels: Explorations through Action Research and Self Study* (pp. 22–25). essay, ISTES Organization. Retrieved 2023, from <https://www.istes.org/teaching-nature-of-science-across-contexts-and-grade-levels-explorations-through-action-research-and-self-study-32-b.html>.
- Khishfe, R. (2007). The development of seventh graders' views of nature of science. *Journal of Research in Science Teaching*, 45(4), 470–496. <https://doi.org/10.1002/tea.20230>
- 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(7),

- 551–578. <https://doi.org/10.1002/tea.10036>
- Kimball, M. E. (1967). Understanding the nature of science: A comparison of scientists and Science Teachers. *Journal of Research in Science Teaching*, 5(2), 110–120. <https://doi.org/10.1002/tea.3660050204>
- Kuhn, T. S. (1975). *The structure of Scientific Revolutions: 2d ed., enl.* University of Chicago Press.
- Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching*, 39(6), 497–521. <https://doi.org/10.1002/tea.10034>
- McClain, J., Cesljarjev, C., Zhong, Q., Rahman, S., Liu, C., Phillips, A., Ariyaratne, T., & Akerson, V. L. (2022). Developing nature of science ideas and orientations at the graduate level: Better late than never. *International Journal on Studies in Education*, 4(2), 155–170. <https://doi.org/10.46328/ijonse.82>
- NSTA. (2020). *Nature of science*. <https://www.nsta.org/nstas-official-positions/nature-science> Olson, J. K. (2018). The inclusion of the nature of science in nine recent International Science Education Standards Documents. *Science & Education*, 27(7–8), 637–660. <https://doi.org/10.1007/s11191-018-9993-8>
- Phillips, A., Rahman, S., Zhong, Q., Cesljarjev, C., Liu, C., Ariyaratne, T., McClain, J., & Akerson, V. (2022). Nature of science conceptions and identity development among science education doctoral students: Preparing NOS teacher educators. *International Journal of Research in Education and Science*, 8(4), 626–646. <https://doi.org/10.46328/ijres.2986>
- Pomeroy, D. (1993). Implications of teachers' beliefs about the nature of science: Comparison of the beliefs of scientists, secondary science teachers, and Elementary Teachers. *Science Education*, 77(3), 261–278. <https://doi.org/10.1002/sce.3730770302>
- Popper, K. (1968). *The logic of Scientific Discovery*. Harper & Row.
- Rothman, S. (2022). College Students' Views of the Nature of Science. In V. Akerson & I. Carter (Eds.), *Teaching Nature of Science Across Contexts and Grade Levels: Explorations through Action Research and Self Study* (pp. 167–190). essay, ISTES Organization. Retrieved 2023, from college-students-views-of-the-nature-of-science-363-s.html.
- Sadler, T. D. (2006). "I won't Last Three Weeks": Preservice Science Teachers Reflect on their student-teaching experiences. *Journal of Science Teacher Education*, 17(3), 217–241. <https://doi.org/10.1007/s10972-005-9004-1>
- Samarapungavan, A., Westby, E. L., & Bodner, G. M. (2006). Contextual epistemic development in science: A comparison of chemistry students and research chemists. *Science Education*, 90(3), 468–495. <https://doi.org/10.1002/sce.20111>
- Scharmann, L. C. (1988). The influences of sequenced instructional strategy and Locus of control on Preservice Elementary Teachers' understanding of the nature of science. *Journal of Research in Science Teaching*, 25(7), 589–604. <https://doi.org/10.1002/tea.3660250706>
- Schwartz, R., & Lederman, N. (2008). What scientists say: Scientists' views of nature of science and relation to science context. *International Journal of Science Education*, 30(6), 727–771. <https://doi.org/10.1080/09500690701225801>
- Southerland, S. A., Gess-Newsome, J., & Johnston, A. (2003). Portraying science in the classroom: The manifestation of scientists' beliefs in classroom practice. *Journal of Research in Science Teaching*, 40(7), 669–691. <https://doi.org/10.1002/tea.10104>


Summers, R., Alameh, S., Brunner, J., Maddux, J. M., Wallon, R. C., & Abd-El-Khalick, F. (2019). Representations of nature of science in U.S. science standards: A historical account with contemporary implications. *Journal of Research in Science Teaching*, 56(9), 1234–1268. <https://doi.org/10.1002/tea.21551>

Survey of earned doctorates (SED)2022. NSF. (2023, September 28). <https://nces.nsf.gov/surveys/earned-doctorates/2022#qs>

Tira, P. (2009). (thesis). *Comparing scientists' views of nature of science within and across disciplines, and levels of expertise*. Indiana University, Bloomington, Ind.

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