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Science & Education
Contributions from History, Philosophy and Sociology of Science and Mathematics

ISSN 0926-7220
Volume 28
Combined 9-10

Sci & Educ (2019) 28:1027-1053
DOI 10.1007/s11191-019-00081-x

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https://doi.org/10.1007/s11191-019-00081-x

ARTICLE

Extending the Utility of the Views of Nature of Science Assessment through Epistemic Network Analysis

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Published online: 4 November 2019

Abstract
An understanding of how science is enacted and how scientific knowledge is generated, or the nature of science (NOS), is a major goal of science education. NOS views have almost exclusively been assessed using the Views of Nature of Science (VNOS) suite of instruments, which consists of open-ended questions. The purpose of this study was to investigate the utility of performing an Epistemic Network Analysis (ENA) from VNOS-B responses, using the group as the unit of analysis. Traditional scoring of the VNOS responses demonstrated that overall, participants shifted from emerging to more sophisticated views across all elements. An ENA provided a quick visualization of how participants connected NOS ideas. With regard to accuracy of participants' NOS understandings as a group, findings from traditional VNOS analysis and ENA converged on two main points, improvement of overall quality of knowledge and the identification of missing elements of NOS from responses. Some changes in participants' NOS understanding were identifiable in results from only the ENA. For example, prior to instruction, ENA showed three naive ideas about empiricism. After instruction, no naive statements remained in the responses about the empirical nature of science. ENA extends the traditional VNOS analysis by enabling the pinpointing of particular ideas that are meaningful to the group, indicating clusters of ideas that are related, and illustrating the way informed, transitional and naïve ideas intermingle.

Keywords nature of science · epistemic network analysis · Views of Nature of Science assessment · assessment

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1 Introduction

At a time when developing a scientifically literate citizenry is increasingly important (Yacoubian 2018), it is critical that K-12 teachers and their students understand how science is enacted and how scientific knowledge is generated, also known as the nature of science (NOS). Indeed, this is a major goal of science education (AAAS 1993; NGSS Lead States 2013). Yet research has focused on learners' understanding of separate NOS elements, largely ignoring connections among these elements. The current study aims to explore how learners make connections among NOS elements, an indicator of deeper conceptualization and expertise (Larkin et al. 1980). As the Views of the Nature of Science Survey (VNOS) has been the most widely used open-ended NOS questionnaire (Abd-El-Khalick 2014; Lederman et al. 2002), this study investigated a way to potentially extend the utility of this instrument. To do this, the VNOS was analyzed both in a traditional way (responses rated holistically as one of three levels for each participant) and in a different way involving Epistemic Network Analysis (ENA), and then results were compared. ENA involves having learners consider collective NOS understanding of a group. It also had the potential to provide additional information such as anchoring ideas, clustering of ideas, and more to enhance the exploration of connections the class identified among NOS concepts.

The development of a scientifically literate citizenry requires teaching both concepts in science and how those concepts are discovered and validated (AAAS 1993; NRC 1996). Emphasis has been placed on instruction regarding the social and epistemic dimensions of scientific knowledge construction (Duschl and Grandy 2008), which include classroom activities that mirror essential aspects of professional science (Ford and Forman 2006; O'Neill and Polman 2004). NOS can be defined as science as a way of knowing, the epistemology of science, or the values and beliefs inherent to the development of scientific knowledge (Lederman 2007). Ideas about what school-age children should know about NOS have been well articulated (Lederman 2007; McComas 2019) and are present in learning standards documents for all 50 states of the United States (McComas et al. 2009) and in many international science education reform documents. Although there are multiple competing ways to conceptualize NOS for K-12 (e.g., Erduran and Dagher 2014, 2016; Lederman 2007; McComas 2008; Osborne et al. 2003b), in the current study NOS was conceptualized in a domain general way, as advocated by Kampourakis (2016), Lederman (2007), and others. The concepts included: (a) empirical evidence is used to support ideas in science (empirical); (b) scientific knowledge is durable yet can change with the addition of more data and/or a change in perspective when considering existing data (tentative/durable); (c) scientific knowledge is a product of both observations and inferences (observation/inference); (d) scientific knowledge is subjective and theory-laden (subjective/theory-laden); (e) science is a creative endeavor (creative); (f) theories and laws play a central role in developing scientific knowledge, yet they have different functions (theory/law), (g) social and cultural factors play a role in the construction of scientific knowledge (social/cultural); and (h) there is no single, universal scientific method (methods). Selecting this conceptualization of NOS allowed the current study to focus on the connections that students made within this one conceptualization. An examination of learners' conceptions across NOS models (as done in Peters-Burton and Baynard 2013) is worthy of investigation, but this was beyond the scope of the current work given its emphasis on the VNOS survey—which is aligned with the selected conceptualization.

2 Literature Review

2.1 Connections among NOS Ideas

Although Lederman and colleagues typically display NOS elements in a list-like format, they do not advocate treating the NOS elements as a list. NOS elements are not separate constructs and have a great deal of overlap and interconnection (Lederman 2007). McComas organized the NOS elements as three subdomains, highlighting connections through the overlapping portions of the diagram (Fig. 1; McComas 2019). The subdomains represent tools and products of science, human elements in science, and special nature of scientific knowledge. Kampourakis (2016) illustrated the many similarities between variations of the "'general aspects' conceptualization of NOS" (p. 670). For example, Lederman (2007) and McComas (2008) highlight creative and subjective elements of science and that science is empirically based yet scientific knowledge can change. The researchers also agree that scientific theories and laws are different yet related forms of scientific knowledge and cultural contexts impact science. McComas has these concepts nested in broader categories (creativity within "Human Elements in Science" and theory/law within "Tools. Processes and Products of Science"). Similar connections were acknowledged in a Delphi study of what NOS ideas should be taught K-12; many experts considered there to be relationships among themes (Osborne et al. 2003a). Within the past decade, there has been some initial consideration of how to assess these connections and relationships. Yet, most NOS research on learners' NOS conceptions and understandings has continued to emphasize individual learners' conceptions separately for each targeted NOS element. The current study addresses this need by using ENA to investigate connections among NOS elements made by a group of learners. Below we review main ways that NOS conceptions have been assessed.

2.2 NOS Assessment

In the words of Abd-El-Khalick (2014), "In a 'real' and practical sense, the only NOS construct (or constructs) in currency in the field of science education is the construct (or are the constructs) being assessed" (p. 621). Therefore, it is of critical importance to consider how NOS can be assessed. In a compilation of NOS assessments, Abd-El-Khalick identified 32 instruments developed from 1954 to 2012. Most of the instruments were forced-choice,

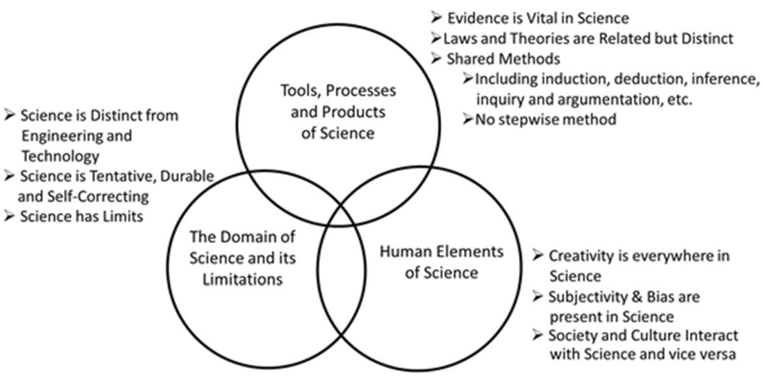

Fig. 1 Nine key NOS elements by related subdomains (McComas 2019, used with permission)

comprised of items such as Likert scale, agree/disagree, or multiple choice. More recently, however, there has been a shift away from forced-choice instruments to instead favor open-ended instruments. Three instruments comprise greater than half of all assessment use over the past six decades: VNOS (Lederman et al. 2002), Test on Understanding Science (TOUS; Cooley and Klopfer 1961), and Views of Science-Technology-Society (VOSTS; Aikenhead and Ryan 1992).

Across forced-choice and open-ended instruments alike, the VNOS suite of instruments received the highest index-of-use rating. Therefore, it seems as though the field has converged on the use of the VNOS suite of instruments to assess NOS conceptions (Abd-El-Khalick 2014; Lederman et al. 2002). Due to the widespread use of this suite of instruments, the current study considered important ways to extend the information that the VNOS provides.

2.3 The VNOS Instruments

The VNOS instruments consist of open-ended questions corresponding to characteristics of scientific knowledge considered appropriate for K-12 science instruction (Kampourakis 2016; Smith et al. 1997). There are various forms with different intended participants. For example, the VNOS-A, B, and C are intended for use with high school students and adults such as science teachers. Additional forms, including the VNOS-D and E, are suitable for younger participants such as elementary students.

The written responses are commonly member checked through a semi-structured follow-up interview (Lederman and O'Malley 1990) with at least 20% of participants, as recommended by Lederman et al. (2002). The open-ended format enables the development of rich profiles of learners' understandings without as much constraint on learners' ideas as in forced-choice instruments (Lederman 1992; Lederman and O'Malley 1990; Lederman et al. 1998). The VNOS instruments also eliminate researchers' predefined positions in the same way that interviews have been used to develop surveys grounded in participant ideas (Ryan and Aikenhead 1992). Recording views as understood by the participant instead of fitting views into an already constructed framework is important (Hammer et al. 2005; Redish 2004). As such, the open-ended nature of the VNOS is considered by many to generate responses that provide authentic, rich ideas about how respondents interpret elements of NOS. Using the same instrument in the same way across studies demonstrates consistency in a field. This has supported a strong NOS research base on explicit, reflective NOS instruction.

Traditionally, a team of NOS experts examine VNOS responses to categorize an individual's conceptions as informed, transitional, or naive for each NOS element. While very helpful for illustrating individual and whole group NOS understanding, the connections among NOS concepts is relegated to the background. There is the potential to also investigate learners' ideas about connections among NOS concepts, a critical yet underexplored aspect of scientific literacy. The current study contributes an initial exploration into using an extension of the VNOS to do this.

2.4 Assessment of Connections among NOS Concepts

Although little research has focused on the connections that learners make among NOS concepts, initial theoretical and empirical work indicates the potential of this area of research (e.g., Akerson et al. 2000; Bartos and Lederman 2014; Hanuscin et al. 2006; Ozgelen et al. 2013). McComas (2019, Figure 1) makes explicit these connections in his graphic representation of NOS through the overlapping subdomains of "Tools, Processes and Products of Science"; "Human Elements in Science"; and "The Domain of Science and Its Limitations." Some researchers have used written and interview responses related to the VNOS and another project-specific open-ended survey, written reflections, and/or concept maps to explore learners' ideas about these connections. For example, Akerson et al. (2000) used VNOS-B written responses, pre/post-intervention interviews, and written reflections to explore elementary teachers' NOS understandings, with implications for connections across concepts. For the written reflections, 50 teachers enrolled in an undergraduate or graduate section of a science methods course were asked to compare readings, videos, and other assignments to class discussions on NOS. One teacher generated a concept map within a written reflection to articulate the relationships among NOS concepts and a course reading. The researchers concluded that very few participants expressed a consistent framework across all targeted NOS concepts. Participants struggled to make connections across elements, an essential part of integrated NOS understanding. Bartos and Lederman (2014) used an open-ended instrument, Knowledge Structure for NOS and SI Questionnaire that the researchers considered to promote clear communication of NOS connections similar to a concept map. They included the identification of any connections among NOS and inquiry concepts in the teacher profiles. The researchers concluded that it was challenging for the teachers to integrate their ideas across NOS and inquiry, despite their strong science content knowledge.

Yet, there is the potential for learners to make these connections and for researchers to assess them. Hanuscin et al. (2006) used VNOS-C responses and related interviews as well as audio recordings of weekly meetings to develop individual NOS view profiles for each undergraduate teaching assistant pre- and post-intervention. Through inductive analysis, the researcher concluded that, for some teaching assistants, making a connection between two NOS concepts supported improvements in their NOS understanding. More specific information on the analyses conducted to identify these connections was not provided. Ozgelen et al. (2013) used VNOS-B written and interview responses and reflection papers as assessments with elementary preservice teachers. The researchers extended the VNOS interview to explicitly draw attention to possible relationships among NOS concepts. For the written reflections, the teachers reflected on one NOS concept per week focused on the course lab activities they experienced. The researchers looked across data sources to identify all statements that illustrated connections among NOS concepts. They concluded that almost all (43 of 45) of the teachers articulated connections among NOS concepts. The connections were more prevalent post-intervention. These studies present initial indications of the potential benefits associated with extending traditional VNOS assessment and analysis to consider connections, work extended by the current study.

Overall, there is a substantial need for further research into the promotion and assessment of connections among NOS elements and associated integrated understandings. The present investigation explores a different way to analyze learners' NOS understandings with an emphasis on these connections, Epistemic Network Analysis (ENA). The study extends NOS analyses by having learners consider the collective NOS conceptions of a group or class as expressed in VNOS responses. It also enhances the exploration of connections that the group identifies among NOS ideas. Analysis of a group's sensemaking of their own VNOS responses offers a collective analytic approach that may have implications for both researcher and teacher NOS assessment. Joint consideration of the outcomes from both traditional VNOS assessment and ENA assessment analyses could facilitate advancements in NOS assessment.

2.4.1 Epistemic Network Analysis (ENA) assessment

Another approach to assessment of NOS views is ENA (Peters-Burton and Baynard 2013; Peters-Burton 2015; Khishfe and Abd-El-Khalick 2002; Peters-Burton et al. 2017). ENA produces a network model of a group's agreed upon statements about ways of knowing and the nature of knowledge. The network model displays nodes representing the epistemic ideas connected by lines that are derived by counting the frequency of pairing of group members' ideas. The use of ENA in examining NOS beliefs of a group of people can potentially identify how participants connect NOS elements, measure the density of clustering among ideas, and indicate ideas that are central or foundational to other ideas.

Although understanding NOS knowledge of individual people is useful, ENA gives us another way to look at epistemic beliefs by measuring the collective beliefs of a group. Since the members of a particular discipline help to define and enact the ways of knowing of that discipline, epistemology can be defined by group level. The group approach can represent the ways members of a culture identify meaningful interactions (Knorr-Cetina 1999). ENA is especially useful in defining the cultural epistemology, as it uses the agreed-upon ideas and strengths of the connections across ideas for the group to determine the collective perceptions of the group (Hanneman and Riddle 2005).

An ENA requires two procedures: (a) participants first answer an open-ended questionnaire to generate authentic and rich ideas in the participants' words and (b) participants sort the statements into piles that are meaningful to them. Once responses are written on the open-ended questionnaire, they are open-coded qualitatively by researchers (Strauss and Corbin 1998). Each of the open-coded statements are treated as separate "cards" for the participants to sort. In order to reduce redundancy in the statements, similar statements are condensed as seen in Table 1. Each individual statement coded from the whole group is then placed onto an electronic card using an online software package, such as ProvenByUsers.com, and compiled. The collection of electronic cards generated from statements for the entire group are then returned to the participants for sorting. Each participant is instructed to independently sort the statements into piles that make meaning for them (Weller and Romney 1988). This card-sorting technique has been used in the field of cognitive psychology, specifically with the Wisconsin Card Sorting Task, which is used to determine competence with abstract reasoning. This card-sorting technique is also used by website designers for usability tests, instructing

Table 1 Example of duplicate statements and resulting statement for card sort

Verbatim statements from VNOS responses	Condensed statement for ENA card sort
A theory CAN change, but since it is backed up by so much evidence and has been tested repeatedly and maintained its 'trueness', we teach it as the best explanation. If something new were to be discovered, tested, and found to be true, we can alter or change a theory.	A theory CAN change, but since it is backed up by so much evidence and has been tested repeatedly and maintained its 'trueness', we teach it as the best explanation.
Theories can and are disproved from time to time or are edited to reflect the most currently reviewed research or technology.	
Theories do change over time because new discoveries are always being made.	
Yes, theories can change as additional knowledge is gained that changes our understanding of natural processes.	

potential users to group together items that belong together for the purposes of designing navigation (Kaufman 2006).

During the card-sorting portion of an ENA, the participants are given instructions to leave out cards they do not understand or believe are incorrect. The software collects pairings of the cards across the group from the piles and compiles the number of times the statements are placed together for all members of the group. For example, if two ideas (card #X and card #Y) were put into the same group 14 times across 25 responses, the cell that was in row X, column Y was marked with a 14. The pairs of statements that were placed together most frequently by the group are considered more closely connected. Each statement that is chosen by participants during the card sort forms a node, and connections between the nodes represent how the group understands the interconnectedness of the concepts. Counts of the pairs of statements for each participant are entered into network software, such as UCInet, and the result is a network model (e.g., Fig. 4) which represents the ways in which the group connects ideas from open-ended responses. Ideas that are most connected to other ideas are represented by nodes located centrally on the network model, and ideas that participants found more related form clusters. The strength of the connectedness of ideas is indicated by the distance between nodes. Beliefs closer together on the network model are perceived as more similar, while beliefs further apart are perceived as more dissimilar by the group as a whole.

Previous ENA studies have examined participants' collective epistemological views of science using researcher-created, open-ended questions to generate statements. This study used the VNOS-B to collect the open-ended responses, in order to potentially extend the utility of the most widely used NOS open-ended assessment.

2.4.2 Research Questions

The current study focused on students in a graduate course on NOS and was driven by the following research questions:

- RQ1: To what extent did the group understand selected NOS concepts pre- and post-course, as indicated by "traditional" rating of participant VNOS responses?
- RQ2: In what ways did the group make connections among NOS concepts, as illustrated by an ENA model derived from participants' pre- and post-course VNOS responses?
- RQ3: How do the results for traditional VNOS analysis and ENA compare?
- RQ4: What are the benefits and drawbacks of administering the VNOS assessment with an ENA extension?

3 Methods

This study was exploratory in nature and took the form of a conversion mixed methods design (Teddlie and Tashakkori 2009). The design converted qualitative data collected from the open-ended responses of the VNOS into quantitative data based on frequency of pairing ideas across the group of participants. The quantitative data were used to form a visualization, called a network model, representing the frequency of connectedness between statements. Details of the method are explained in the procedure section below.

3.1 Participants

The participants in the study were 23 graduate students. Sixteen were pre-service secondary science teachers, who took the course prior to their student teaching, and the other seven were elementary in-service teachers who had an average of 7.6 years of experience. Seven were male and 22 were white, one was Asian. The sample was a convenience one, since it consisted of all of the students taking a graduate-level NOS course. As the goal of this study was to consider how a VNOS instrument could be extended through the addition of ENA, use of a convenience sample is appropriate for this initial exploratory study.

3.2 Professional Development Course

The master's level course that informed students NOS views took place over 16 weeks. It was structured as an asynchronous online course focused on various NOS models. These included models by Lederman and colleagues (e.g., Lederman 2007), McComas (e.g., McComas 2008, 2019), and a Family Resemblance Approach model (e.g., Erduran and Dagher 2014, 2016). Teachers were required to apply one or more NOS models to their lessons using an explicit and reflective approach in science lessons. The course relied primarily on the NOS model and associated NOS elements of Lederman (1992) and McComas (2008) to guide instruction and were treated as "expert frames" or external reference points that explicitly describe the characteristics of scientific knowledge. The selection of a primary model allowed congruence between the intervention, the instrument used to assess students' NOS understandings, and the associated analyses. It was beyond scope of this project to consider understandings across NOS models.

The students in the class read several educational research articles on the use of explicit and reflective NOS instruction and applied the techniques from these articles into their lessons by videoing the implementation of the lesson. Students then peer reviewed each other's videos. Students videotaped their improved explicit, reflective implementation based on the feedback from the peer review. A final reflection of the implementation of explicit, reflective NOS instruction was posted on a discussion board. The focus of the current study was not on the effectiveness of the course, but on the type of information gathered by analyzing VNOS-B responses using an ENA.

3.3 Procedures

All 23 teacher-participants took the VNOS-B before and after the 16-week NOS course, which contributed to the consistency between the pre- and post-course network models. In other words, the pre- and post-course network models were comparable because they represented exactly the same people in both cases. Students were instructed to take the VNOS-B in an electronic form that deposited their responses into a spreadsheet. According to the time stamps in the form, the participants took from 20 to 43 minutes to complete the VNOS-B across the two administrations.

3.3.1 Traditional Coding of the VNOS-B Responses

Pre- and post-course VNOS-B responses were also traditionally coded and categorized holistically, per participant, as one of three possible levels (informed, transitional, or naïve).

For example, a response categorized as informed for the durable yet tentative nature of scientific knowledge addresses how much evidence can support scientific knowledge and, through peer review and repeatable outcomes, the scientific community can be increasingly confident in conclusions. Yet a strength of science is that scientific knowledge can change if needed based on the examination of existing data through a different perspective or the collection of additional data. A response categorized as naive emphasizes an extreme view that scientific knowledge is absolute or always changing. A response categorized as transitional included references both to absolute knowledge and how it can change. Cohen's K was calculated to determine interrater agreement for VNOS responses. There was substantial agreement for pre-course ($K = .764$, $p = < .0005$) and post-course ($K = .854$, $p = < .0005$) responses.

3.3.2 ENA of VNOS-B Responses

All participants' responses from the VNOS-B were open-coded and fragmented into separate statements that each had stand-alone meaning (Strauss and Corbin 1998). The pre-course VNOS-B administration generated 45 NOS-related statements (Appendix Table 6), whereas the post-course administration generated 41 NOS-related statements (Appendix Table 7). Coding was done by the first author and was checked for interrater reliability by a graduate student independently coding 30 % of the VNOS-B participants' responses. The coding choices were discussed until consensus was reached. Discussion largely focused on duplicate statements, resolved by removing repetition. Table 1 displays an example of the protocol for duplicate statements. The remaining 70 % of the coding was adjusted based on this consensus conversation.

Each coded statement was entered into the software package, Proven By Users. This software situated the statement as movable "cards" that could be dropped and dragged into separate electronic "bins." Participants were instructed not to place statement cards into bins if they did not agree with and/or understand the statement. Only the statement cards that were placed in a bin were used in the quantitative conversion, which is the reason that the numbers of the statements in the appendices are not sequential.

Placement of the statement cards by the participants into a virtual bin resulted in a unit matrix that represented the pairing of the cards. The frequency of pairings was represented quantitatively in the following way. If card 6 and card 15 were both placed in bin A, then a "1" would be placed in row 6, column 15 and row 15, column 6. Once all possible pairings from one person were recorded, the resulting unit matrix represented his/her statement sorting. All unit matrices for all participants were added together. Zeros remained in the cells for the statements that were never paired together. The frequency of pairing cards appeared across the group in the other cells, with the maximum number being 23.

The summed pre-course matrix was placed into UCInet, a network model generation software. The software maps statements as nodes and connects paired nodes with line segments. A network model can indicate three characteristics of mapped data: (a) the ideas that are most connected to other ideas, indicated by centrally located nodes on the network model; (b) how ideas are regarded as related, indicated by clusters of nodes on the network model; and (c) strength of connections among ideas, indicated by the distance between nodes where short distances represent stronger connections (Kruskal 1964). Multidimensional scaling was used to assign locations to nodes such that nodes that are more frequently associated together by students in the group are located closer together on the network model as a cluster.

Then, statements were individually rated as naïve, transitional, or informed by the authors (Tables 2 and 3). Statement rating initially had an 80% agreement among the three authors. Consensus was reached through discussion. Additionally, authors independently identified the major NOS element in each statement, with 83% agreement among the three authors. Again, consensus was reached through discussion. Appendix Table 6 (pre-course) and Appendix Table 7 (post-course) display the statements, ratings, and major NOS elements identified. Nodes on the network model were color coded according to major NOS element. Increased node size corresponded to increased statement accuracy; small nodes represent naive statements, medium nodes represent transitional statements, and large nodes represent informed statements.

4 Findings

The present investigation aimed to consider the potential of an ENA extension to VNOS assessment administration. To do so, we first examined pre/post-course results of traditional VNOS analysis and ENA separately. Then we compared the results of the two analyses. Finally, we considered the potential additional value of this ENA extension beyond traditional VNOS analysis.

4.1 RQ1: To What Extent did the Group Understand Selected NOS Concepts Pre- and Post-Course, as Indicated by "Traditional" Rating of Participant VNOS Responses?

4.1.1 Pre-course Assessment

Before the course, traditional VNOS-B analysis indicated that participants tended to hold naive to transitional understanding on six of the eight selected NOS elements (Fig. 2). In particular, participants overemphasized the role of experiments in the development of scientific knowledge, universality, and considered subjectivity in science to be either nonexistent or something negative to be avoided in any way possible (Table 4). Participants also tended to overemphasize the role of observations in the development of scientific knowledge. For two NOS elements, the empirical nature of scientific knowledge and the roles of scientific theories and law, more participants held informed understandings.

Table 2 Ratings of pre-course network model statements derived from group's VNOS-B responses

NOS Element	Pre-course Ratings			
	Naive	Transitional	Informed	Total
Empirical	1	2	1	4
Tentative/Durable	2	1	0	3
Observation/Inference	1	3	0	4
Subjective/Theory-laden	4	1	1	6
Creative	3	5	0	8
Theory/Law	10	4	1	15
Social/Cultural	1	0	0	1
Methods	1	3	0	4

Table 3 Ratings of post-course network model statements derived from group's VNOS-B responses

NOS Element	Post-course Ratings			
	Naive	Transitional	Informed	Total
Empirical	0	1	0	1
Tentative/Durable	0	4	0	4
Observation/Inference	1	2	0	3
Subjective/Theory-laden	0	3	4	7
Creative	4	7	1	12
Theory/Law	3	7	3	13
Social/Cultural	0	0	0	0
Methods	0	0	1	1

4.1.2 Post-Course Assessment

After the course, traditional VNOS-B analysis indicated that the percentage of participants holding more informed understandings increased for each selected NOS element (Fig. 3). In particular, there were substantial improvements in the group's understanding of subjectivity / theory-laden nature of science (61% informed) and creativity (57% informed). Participants identified more and more informed descriptions of influences on science, considering individual and societal differences in perspectives, values, interests, disciplinary background, and experiences. Participants also developed more nuanced understanding of creativity in investigations beyond experiments and experimental design. There was more room for growth for social/cultural influences on science and methods, with 17% of participants holding informed conceptions on social/cultural influences and 26% for methods. Participants tended to focus largely on technology as an example of social / cultural influences. They also continued to overemphasize the role of experiments in the development of scientific knowledge. See Table 4 for representative post-course statements.

Traditional rating of the VNOS responses showed that, overall, participants shifted from transitional to more informed understandings across all elements (Table 5). There were only eighteen instances of participants holding a naïve conception on any of the NOS elements, representing only 9 % of participants with any naïve conceptions post-course.

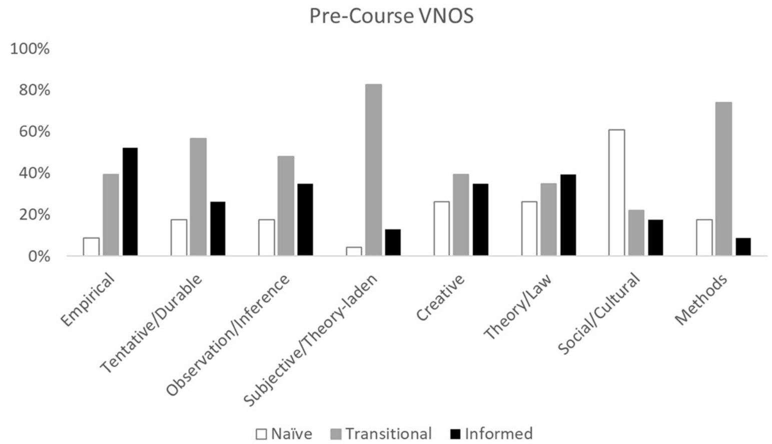

Fig. 2 Summary of group's pre-course VNOS rating for each selected NOS element

Table 4 Representative participant VNOS responses for each assessed NOS concept, categorized as naive and informed

NOS element	Pre-course*	Post-course*
Empirical	Theories can change as additional knowledge is gained that changes our understanding of natural processes. …. An example of a theory that has changed includes the theory of evolution by natural selection, which has been deepened by greater understanding of the function of DNA and how new traits (that may or may not be advantageous for survival) can emerge to be selected for or against. … Scientific knowledge is based upon evidence that is the result of repeated observations (whether gathered through experimentation or through observing natural phenomena). (Informed, Jocelyn)	Theories can and do change as we are able to make deeper observations of the world around us. Sometimes those new observations cause us to entirely discredit an old theory, and other times, an old theory is modified to better fit with the new observations and evidence. … One example of a theory changing with new evidence is the theory of plate tectonics explaining the movement of the earth's land masses over the ages. Previous thinking held up until the ability to map the ocean floor (among other things) discredited previously held ideas to the point that a newer explanation had to be developed to explain the distribution of common features across continents and the "puzzle-piece" type fit of the continental shelves. (Informed, Jocelyn)
Tentative/Durable	As more data becomes available theories are subject to revision. My favorite example is the theory of plate tectonics. The precursor, continental drift, was developed but lacked some key pieces of evidence. Once data was available to support this theory it became accepted within the scientific community. Transitional, Kathy)	As new technology brings more and better data, theories are subject to revision. Even though theories are subject to change they are thoroughly tested, evidence based and at the time are agreed upon by the scientific community. In geology, the geosyncline theory used to be the accepted theory behind mountain building. We now know it to be false. (Informed, Kathy)
Observation/Inference	I have often thought astronomers have great imaginations given the graphics of various distant objects and phenomena they theorize about. This is clearly an area where imagination is used in conjunction with observable and quantifiable observations to construct objects that are simply unavailable for direct examination, at least to the degree other more earthly phenomena are. There are likely other areas of inquiry as well, the structure of the atom is another example cited above, chemistry and how it works is another, what dinosaurs looked like etc. Many phenomena cannot be directly observed and are inferred based on information from the experimental system. (Informed, Evan)	My favorite topic is cosmology where scientists have extend our senses with remarkable telescopes, radiation detectors, and "time machines" to look into the distant galactic past. … Then scientists come up w some of the most creative explanations and physical models for their observations, e.g. black holes, something that cannot be seen because the density is so high even light can't escape. (Informed, Evan)
Subjective/ Theory-laden	I think there is an idea of bias at play here. When you look at data, you are likely to see what you want to see. (Naive, Rose)	While the empirical data are the same, the theories that explain the data are not. It seems as though we need more evidence to support one of the theories listed above; right now, the evidence can be interpreted to support all three. (Transitional, Rose)

Table 4 (continued)

NOS element	Pre-course*	Post-course*
Creative	I think that depending on the experiment, scientists have to be creative with data collection methods. An example would be collecting samples out in the field but there are a number of obstacles in their way so they have to be creative in figuring out how to get the data. (Transitional, Shannon)	Scientists can be creative in coming up with models and ways to exhibit knowledge as well as data. They also might need creativity when it comes to interpreting some data/results. (Informed, Shannon)
Theory/law	The current theory of evolution that is accepted today only came about as there were many competing theories on how evolution takes place in nature. The "correct" theory was not the one that made the most sense but rather the theory that was backed up by the most research and evidence. (Transitional, Eric)	Every theory is deeply rooted in evidence and experimentation. Every theory is as valuable as the evidence used to back it up. A scientific theory explains why or how a phenomenon happens while a scientific law explains what is occurring in a phenomenon. The law of gravity states that a particle has an attraction to every other particle in the universe based on the mass of the particle and the distance between particles. The theory that best explains this phenomenon is the theory of relativity which states that gravity is not so much a force but a product of the "bending" of spacetime. (Informed, Eric)
Social/cultural	n/a [no statements referencing social or cultural influences] (Naive, Colin)	Theories change as new data invalidate or justify the alteration of previously held explanations. Geosynclinal theory posited that mountains form as sediments deposited in basins weigh down and warp the crust. Continental drift theory was developed to explain a trove of evidence that suggested that continents were one, during at least episode of Earth's history. It was rejected mostly for political reasons (see Naomi Oreskes "The Rejection of Continental Drift") attached to the fact that a mechanism still needed to be explained. Technological developments allowed for data to be collected that could be used to propose a mechanism, which eventually allowed for the development of Plate Tectonic Theory. (Informed, Colin)
Methods	Climate Change. The scientific knowledge is that it is happening. There is evidence that I can point to that proves it...current goings-on and historic data. (Transitional, Sonya)	[Plate tectonics] is a theory that has developed over time and has benefited from new evidence continually added to the mix. What started as an idea about shapes fitting together was defended by similar rock formations, striations, and fossils across an ocean, was further defended by seafloor spreading, and was further defended by GPS tracking. (Informed, Sonya)

*NOS categorizations were informed by a holistic analysis of all VNOS (Form-B) statements for a given participant for a given condition (pre, post). The statements above represent only a portion of the evidence used to support the categorizations.

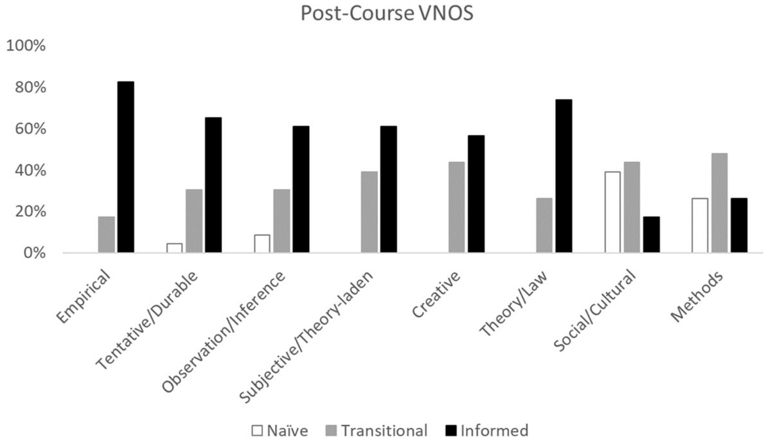

Fig. 3 Summary of group's post-course VNOS rating for each selected NOS element

4.2 RQ2: In What Ways did the Group Make Connections among NOS Concepts, as Illustrated by an ENA Model Derived from Participants' Pre- and Post-Course VNOS Responses?

4.2.1 Pre-course Assessment

Participants generated 45 statements (see Appendix Table 6) derived from the VNOS into an average of 4.96 piles (SD = 1.12). The average density of the pre-course network model (Fig. 4), measured by the number of connecting lines in randomly selected areas of the entire map selected automatically by UCInet, was an average of 7.522 lines (SD = 12.193). The ENA pre-course network model displayed no central ideas, indicating that there were no NOS ideas helped to frame the remaining NOS ideas for the participants prior to the class.

Sometimes patterns within clusters of nodes are discernable, displaying one or two informed statements which anchor surrounding less informed statements. These visual patterns could be a representation of participants connecting less evolved ideas with stronger foundational ideas. The major clusters of statements, as seen to the left top side of Fig. 5, represented a variety of ideas about NOS. This was expected in a pre-course assessment, since novices

Table 5 Number of participants categorized at each level of NOS understanding for each element pre and post course

	Pre-course			Post-course		
NOS Element	Naive	Transitional	Informed	Naive	Transitional	Informed
Empirical	2 (9%)	9 (39%)	12 (52%)	0 (0%)	4 (17%)	19 (83%)
Tentative/Durable	4 (17%)	13 (57%)	6 (26%)	1 (4%)	7 (30%)	15 (66%)
Observation/Inference	4 (17%)	11 (48%)	8 (35%)	2(9%)	7 (30%)	14 (61%)
Subjective/Theory-laden	1 (4%)	19 (83%)	3 (13%)	0 (0%)	9 (39%)	14 (61%)
Creative	6 (26%)	9 (39%)	8 (35%)	0 (0%)	10 (43%)	13 (57%)
Theory/Law	6 (26%)	8 (35%)	9 (39%)	0 (0%)	6 (26%)	17 (74%)
Social Cultural	14 (61%)	5 (22%)	4 (17%)	9 (39%)	10 (44%)	4 (17%)
Methods	4 (17%)	17 (74%)	2(9%)	6 (26%)	11 (47%)	6 (26%)

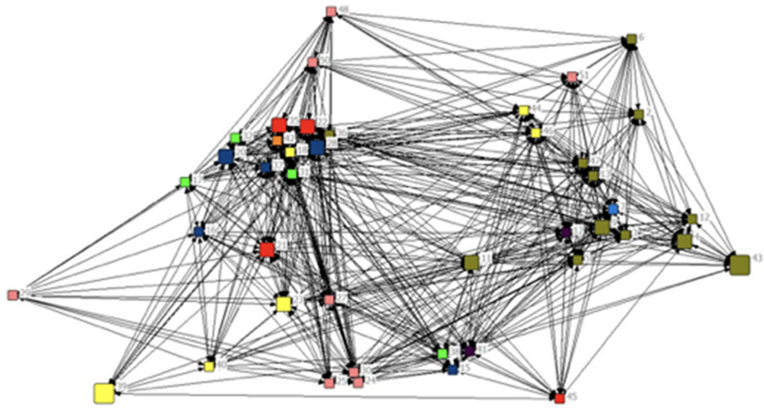

Fig. 4 Pre-course ENA network model

have difficulty distinguishing unfamiliar ideas (Anderson 1981; Larkin et al. 1980). These varied ideas included knowledge about atoms, creativity, and aims of science. Participants' ideas also did not have a hierarchy in the organizing structure. This, again, is characteristic of novices (Anderson 1981; Larkin et al. 1980). There is another cluster on the right side of the network model displaying many ideas about theories and laws. This cluster it is not as tightly connected, and the statements were mostly naive. Note that a sophisticated statement (#43) anchors this loose cluster, "A scientific theory takes a collection of discovered/known findings and posits an explanation for the phenomenon being explained to the time it's proposed. A scientific law dictates how something works or a specific relationship between things that appears to be consistent across phenomena." There are two other occurrences of a sophisticated statement anchoring other loose smaller clusters (#39, #20, and #28). These two clusters both focus on the same NOS element, theories and laws. This may indicate that the participants collectively are forming a network of ideas about theories and laws. This may be the first NOS element about which participants' ideas are more connected, as compared to the others.

In the major cluster to the left top of Fig. 5, there are two sophisticated statements about multiple methods in science. These statements anchor the assortment of other transitional and

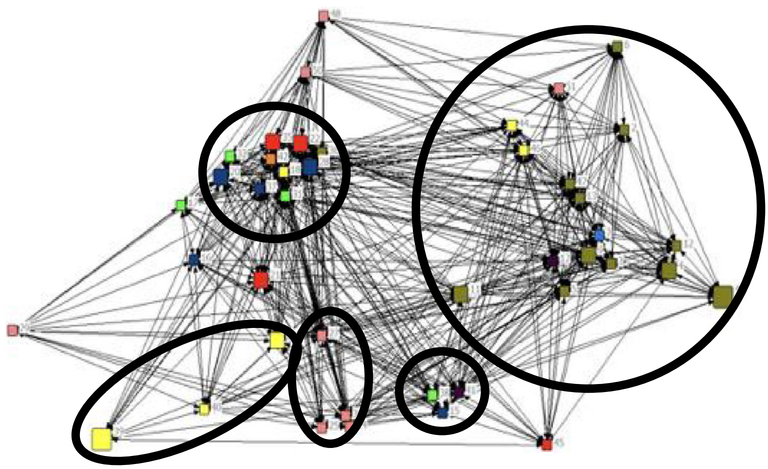

Fig. 5 Pre-course ENA network model with clusters noted

naive statements in that cluster (empirical, subjective, theories and laws, creative, and observation/inference). The varied NOS elements addressed by these statements may indicate that the statements about methods help participants think about other NOS elements, such as when scientists are creative in choosing from multiple methods, or that there is subjectivity in science due to the choice of methodology.

Additionally, three smaller clusters were present on the pre-course network model. These clusters represented ideas about (a) subjectivity (#39, #40, and #23), (b) creativity (#27, #30, #25, and #24), and (c) an assorted cluster on empiricism, methods, and tentativeness elements (#38, #15, and #41). The statements were largely naive. Participants did not make clear connections for tentative or social/cultural elements of NOS.

4.2.2 Post-course Assessment

Participants generated 41 statements (see Appendix Table 7) derived from the VNOS into an average of 6.14 piles ($SD = 3.32$) with an average density of 9.467 lines ($SD = 14.264$). This is an increase in the piles of statements and in the proximity of distance between statements from pre- to post-course, potentially indicating an increase in the complexity of participants' understanding (Anderson 1981; Larkin et al. 1980). The ENA post-course network model (Fig. 6) also displayed no central ideas, indicating that there were no anchoring NOS ideas after the class. The statements were more informed compared to the pre-course assessment, as indicated by the increase in the size of many nodes (Table 3).

Overall, there were three clusters identified in the post network model (Fig. 7). The clusters in the post-course network model were more distinct and coherent than in the pre-course model. This pattern of distinct clusters indicates that the participants consider statements in one cluster different from statements in another. There is also a dominant NOS element within clusters as compared to the pre-course network model, demonstrating coherence in the cluster. There also were more clusters with multiple, distinct NOS elements in each cluster. Two clusters that were tightly connected represented ideas about creativity and subjectivity (see left side of Fig. 7). Like the pre-course network model, the clusters were anchored by sophisticated statements from other NOS elements. The top left cluster had a majority of statements focused on subjectivity. There also was a sophisticated statement about theories and laws and a transitional statement about empiricism. This implies that students considered subjectivity in

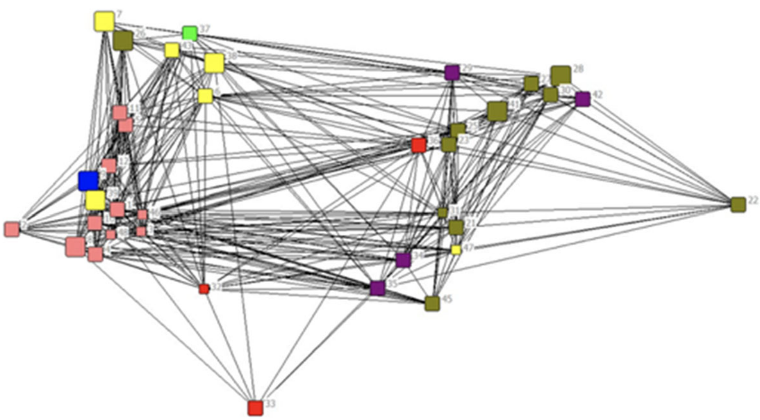

Fig. 6 Post-course ENA network model

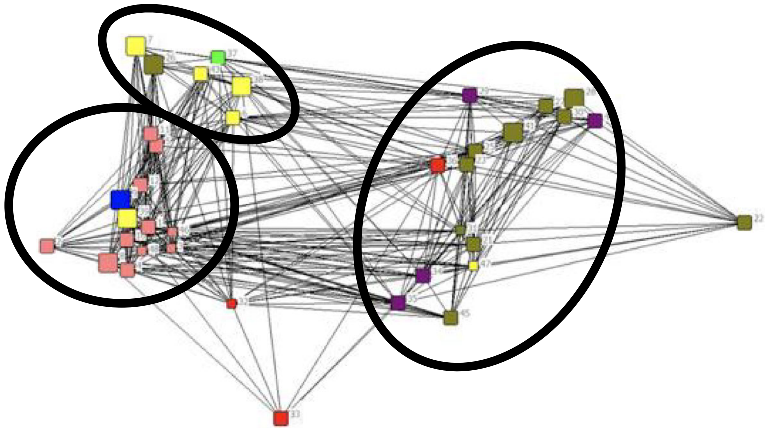

Fig. 7 Post-course ENA network model with clusters noted

science to be connected to ideas about how theories are developed with empirical evidence, as this evidence is sometimes subjective.

The bottom left cluster focused almost entirely on creativity. Yet the cluster was anchored by a sophisticated statement about methods and subjectivity, which represent two sources of creativity in science. It is notable that in this cluster, the more sophisticated statements about creativity are closer to the methods statements. The subjectivity statements and the naive creativity statements were outside of the cluster. Participants may have been able to connect more statements from pre-course test to post-course test, indicating a shift toward more expert-like thinking (Anderson 1981; Larkin et al. 1980).

One more loosely-connected cluster is located to the right in Fig. 7. This cluster mainly represented ideas about theories/laws and tentativeness. Since theories can change with new evidence or new ideas, it is not surprising that these NOS concepts are included in the same cluster. One statement about theory/laws was set apart (#22): "Theories are like gladiators. They compete to see which one fits the bill best." This statement is an analogy that is not clearly connected to the idea of theories, potentially explaining why it is set very far from the other statements. There was one statement about observation/inference included in this cluster. Two additional observation/inference statements were not well connected with any cluster (#36, #32, and #33). This indicated that it may have been difficult for participants to connect observation/inference to the other ideas.

Like the pre-course network model, in the post-course model tentativeness and social/cultural elements were not prominent. Statements about theories, not in relation to laws, were more connected than statements about laws. Statements about creativity were very strongly connected, indicated by an average density of 12.7 lines in that cluster which was higher than the average line density across the map (m = 9.46).

4.3 RQ3: How do the Results for Traditional VNOS Analysis and ENA Compare?

Both analyses included an assessment of the accuracy of participants' NOS statements, using three categories. The traditional analysis of VNOS-B responses assessed each participants' NOS understandings through holistic analysis of a participant's responses to all questions, then summarized percentages of participants categorized at each of the three levels for each NOS concept; this provided a snapshot of the group's understanding pre- and post-course. For ENA, researchers categorized each statement used for the pre- and post-course card sorts.

With regard to the accuracy of participants' NOS understandings as a group, findings from traditional VNOS analysis and ENA converged on two main points. First, participants' statements about NOS improved in overall quality from before to after the course. The alignment was clearest for two NOS elements, creativity and theory/law. In addition, the two analyses agreed that participants' understanding of social/cultural embeddedness remained at naive to transitional levels after the course. This aligns with previous NOS research, for which understandings of the impacts of society and culture are particularly resistant to change (e.g., Abd-El-Khalick et al. 1998; Demirdogen and Uzuntiryaki-Kondakci 2016; Mesci and Schwartz 2017).

Results from the two analyses differed in some ways as well. Some changes in participants' NOS understanding were identifiable in results from only one of the analyses. For example, prior to instruction, ENA showed three naive ideas about empiricism in a cluster of many NOS ideas (#32, #17, and #31). After instruction, no longer were there naive statements about the empirical nature of science. The group understood and agreed upon one transitional idea (#37) about the need for scientific knowledge to be reproducible and based on high quality evidence that is robust enough to withstand critique. This extends the traditional VNOS analysis by enabling the pinpointing of particular ideas that are meaningful to the group.

4.4 RQ4: What are the Benefits and Drawbacks of Administering the VNOS Assessment with an ENA Extension?

ENA offered benefits beyond those of traditional-only analysis of the VNOS assessment. First, ENA produced pre- and post-course network models, which offered quick visualizations of how participants connected NOS elements. Also, there remained no centrality across NOS elements post-course, which indicates that the participants did not view any of the NOS statements as being central to the other ideas. This is important, as central ideas indicate movement toward expertise (Larkin et al. 1980). As shown in other studies using ENA to determine group's views of NOS, scientists' ENA map showed four central ideas, whereas teacher and student maps did not show any central ideas in their views of NOS (Peters-Burton 2015). Additionally, the density of the network models increased from pre-course to post-course, indicating that more ideas were associated with each other (Anderson 1981). The network models indicated how the group's thinking about NOS became more organized. From pre- to post-course, participants elaborated on and improved their organization of theory/law and creativity. This was reflected in the movement of disparate ideas in the pre-course network model to clusters of ideas focused on same NOS elements post-course. High quality NOS statements tended to anchor clusters. Lastly, ENA helped the researchers to identify weaknesses in participants' post-course NOS understanding not identified through the traditional analysis. Despite additional clusters post-course, weak relationships among many NOS elements remained from pre- to post-course.

Although the network models of ENA provide information that went beyond a VNOS assessment, there are several drawbacks of extending the VNOS assessment with an ENA. First, performing an ENA requires a coding process that is different from the evaluation of statements for the traditional VNOS, which can be labor intensive. The coding of statements for ENA cards requires unidimensionality of the statement, which typically fragments ideas rather than drawing upon the richness of answers in a traditional VNOS assessment. Second, extending the VNOS using an ENA requires a degree of specialization in using the software. Third, to determine the size and color of the nodes in an ENA, the researchers must run an additional analysis on the unidimensional statements, and sometimes must make difficult decisions as to which element of NOS best characterizes a statement. Lastly, there is still a question about how and if the exposure to peer's statements during the card sort might impact participant views.

5 Limitations of the Present Study

The present study used a convenience sample for participants. Given that the aim of the study was to explore the potential of ENA, this sample is an appropriate first step. Future research will investigate epistemic network models for experts and those along the trajectory of expertise. The VNOS-B administration did not include post-course interviews as a member check. Future research will explore whether the addition of participants' interview responses change the number and/or content of statements consolidated for ENA. For ENA, the researchers condensed and consolidated participant statements across the entire group to represent non-repetitive ideas of the group. The wording of the final consolidated statements may influence participants' grouping of the statements and thus the clustering. The role of statement length and key words on participants' grouping still needs to be investigated. Also, the condensed statements remove much of the rich context provided in participants' VNOS responses. As rich context may promote and illustrate connections among NOS concepts, it may be helpful to also conduct analyses of these connections within the VNOS responses of each participant to further develop findings on NOS connections. The current study limited the consideration of NOS connections to NOS elements within one NOS conceptualization.

6 Conclusions and Implications

This investigation contributes to NOS research by considering the knowledge gained from adding ENA to existing traditional VNOS analysis. The VNOS has been used almost exclusively in the past 10 years to assess NOS views, allowing researchers to compare outcomes across studies using the same version of the questionnaire. Traditional VNOS analysis has highlighted rich, descriptive change per participant (e.g., Abd-El-Khalick and Akerson 2009; Bell et al. 2016) and per group (e.g., Bell et al. 2016; Mulvey and Bell 2017) to describe pre- and post-intervention change. In the present investigation, this allowed researchers to identify shifts in conceptual understanding in most but not all targeted NOS concepts. Despite the ability to identify these shifts, a main limitation of this traditional analysis of VNOS responses is that results did not provide information about the connections participants made among NOS ideas.

The results of this study provide a distinctive interpretation of a well-known instrument (VNOS-B). The technique of ENA offers insight into the quality of participants' conceptions of NOS and how the group connects NOS elements. Research in the field of NOS has been criticized as focusing on a laundry list of things to memorize (Clough 2007; Herman and Clough 2016). ENA is a unique analysis of the connections among validated results of the VNOS-B. This type of analysis could inspire other ways to capture and examine how the concepts of the nature of science are interconnected and which ones are attainable to particular populations. This may support the development of ways to best scaffold the complex undertaking of learning about NOS for varied learners in different contexts.

Assessing NOS is a difficult task, and ENA may offer a different perspective on capturing knowledge of groups, which includes the interconnectedness of ideas. Considering connections can extend the utility of existing NOS instruments and improve researchers' ability to learn about participants' NOS understandings.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Table 6 Pre-course statements (45) for network model from VNOS-B administration with researcher rating and main NOS element

Statement from pre-course VNOS responses	Rating	Major NOS element
1. A theory can be revised while a law is considered an observable truth that is not amenable to change.	N	Theory/Law
2. Theories don't necessarily change but are modified into new theories so that both the old theories and new theories exist simultaneously.	N	Theory/Law
3. A law states what always happens under certain conditions (often expressed in a mathematical formula) whereas a theory is a widely accepted explanation of a natural phenomenon.	N	Theory/Law
4. A scientific law describes what we observe while a scientific theory is more of an explanation about what we've observed.	Tr	Theory/Law
5. Astronomers can have different conclusions because the universe's state is a theory. There is no way to completely prove any of the statements to be true because there is not enough data for the theory to be made a law.	N	Theory/Law
6. Theories are just based on hypothesis that have not been disproven yet and have documented evidence to support them within the scientific community.	N	Theory/Law
7. Laws deal with mathematics and statistics. A theory is done via experimentation, but is not always consistently found to be true	N	Theory/Law
8. Laws are, for example, the Law of Thermodynamics, which is a mathematical relationship that has always proven to be true. Theories are based on researched hypothesis, however they are not accepted as being true always.	N	Theory/Law
9. A theory is in essence an explanation in process.	Tr	Theory/Law
10. A theory is an explanation, a law is a description that has not been contradicted.	Tr	Theory/Law
11. A theory CAN change, but since it is backed up by so much evidence and has been tested repeatedly and maintained its 'trueness', we teach it as the best explanation.	Tr	Theory/Law
12. An opinion can be about scientific information, theories, or laws; however, scientific knowledge is what scientists know like facts and what is true or false.	N	Tentative/Durable
13. A law is something that is supposed to be correct and explains what happens but not why or how. A scientific theory consists of one or more hypotheses that have been tested	N	Theory/Law

Table 6 (continued)

Statement from pre-course VNOS responses	Rating	Major NOS element
15. Science uses experimental design to prove the understanding of the world around us	N	Methods
17. Science is evidence-based, and is in search of absolute truths.	N	Empirical
18. Scientists cannot just re-interpret the results to match expectations.	N	Subjective/Theory-laden
20. Science aims to understand the world around us. We want to be able to recreate aspects that we able to observe.	Tr	Methods
21. Scientists need to find the best way to show their data and to make sense of what the data shows.	Tr	Observation/Inference
22. Science requires attention to detail.	Tr	Observation/Inference
23. Astronomers from different backgrounds may look at data differently	Tr	Subjective/Theory-laden
24. Creativity is important as you're gathering your data you have to start envisioning how it all fits together.	Tr	Creative
25. Science requires considerable creativity in order to interpret the meaning of data.	Tr	Creative
27. Scientists use creativity to formulate ideas and models to help explain nature.	Tr	Creative
28. Depending on the experiment, scientists have to be creative with data collection methods.	Tr	Methods
29. In science, that creativity and intuition may be the ability to see things in ways that others have not	Tr	Creative
30. Creativity is essential in science	Tr	Creative
31. The evidence scientists used to determine the structure of the atom came from experimental results.	Tr	Empirical
32. Scientists are continuously researching and studying atoms to determine exactly what it looks like.	I	Empirical
35. Science feeds off the curiosity of observation.	Tr	Observation/Inference
36. Scientists are not completely certain about what an atom looks like. This is only a theory. We do not know all of the hard facts.	N	Theory
37. Data collecting needs to be precise in order for the data to be accurate.	Tr	Methods
38. With more research we determine validity in science.	Tr	Empirical
39. Different individuals put different weights on different or similar observations(data) and hence come up with different interpretations of the same" data"	I	Subjective/Theory-laden
40. When you look at data, you are likely to see what you want to see. It is hard to be truly objective.	N	Subjective/ Theory-laden
41. Science must be tested and proven to be true, while some believe its up for interpretation it typically has to be proven by multiple experiments.	N	Tentative/Durable
42. Scientists use technology to identify the shapes of atoms and forms of the particles.	N	Social/Cultural
43. A scientific theory takes a collection of discovered/known findings and posits an explanation for the phenomenon being explained to the time its proposed. A scientific law dictates how something works or a specific relationship between things that appears to be consistent across phenomena.	I	Theory/Law
44. Scientific knowledge consists of a body of facts we know to be objectively true	N	Subjective/Theory-laden
45. Scientists base the structure on the atomic mass of an element and also what compounds are made from combining different elements together which	N	Observation/Inference

Table 6 (continued)

Statement from pre-course VNOS responses	Rating	Major NOS element
would help with the amount of electrons added or lost.		
46. Science is an objective way to express something abstract	N	Subjective/ Theory-laden
47. Scientific theory cannot be tested, scientific law can.	N	Theory/Law
48. Data collection does not require creativity as there is nothing created, only information recorded during data collection	N	Creative
49. Scientists are not certain of the pattern or appearance of the electrons' orbits.	Tr	Tentative/Durable
50. Scientists would use creativity and imagination DURING data collection only if things were going awry and they had to return to the drawing board.	N	Creative
51. Scientists are not creative because they should be collecting and interpreting the data without bias.	N	Creative

Ratings are naïve (N), transitional (Tr), and informed (I).

Table 7 Post-course statements (41) for network model from VNOS-B administration with researcher rating and main NOS element

Statement from post-course VNOS responses	Rating	Major NOS element
1. Scientists use creativity during data collection because if the procedure produces inaccurate data, then scientists must revise the experimental protocol, which requires creativity.	Tr	Creative
2. Both necessitate the creative process in describing the world around us that we seek to understand. Art showcases it more for the aesthetic while science showcases it more for the intellect. Neither are more important than the other.	Tr	Creative
3. Without scientists being creative and using their own creativity, they would not be able to find all of the research they are able to find. They would also not be able to use the data they find to come to the conclusions they do.	N	Creative
4. Science could be categorized as an art. However, science and art can be different because art is a way to express knowledge, while science is a form of acquiring new knowledge.	Tr	Creative
5. Science and art are similar. They are similar because both are creative. They force you to think differently, consider new ideas, and to be open-minded.	Tr	Creative
6. Scientists may look at the exact same evidence, but the way they interpret it can be different. Also, scientists are continuously doing research on the topic and their conclusions can continue to develop.	Tr	Subjective/Theory-laden
7. Different individuals may interpret similar data in different ways because of what they bring to bear when addressing the data i.e. their prior knowledge, social mores, cultural beliefs.	I	Subjective/Theory-laden
8. Scientists get very creative with experimental design, such as the gold foil experiment to show that atoms are mostly empty space. However, they also use creativity in looking at their data and coming up for explanations when it does not mesh with existing scientific understanding.	I	Creative

Table 7 (continued)

Statement from post-course VNOS responses	Rating	Major NOS element
9. Many different interpretations are created from the viewing of one art piece/data set. Also the methods that are used to create scientific knowledge has the same spirit of experimentation that artists have when looking to create something never seen before using the same materials everyone else has.	I	Methods
10. They are similar because you need to be creative in how you look at different problems. They differ though because science is explaining natural phenomenon while art is more for show.	Tr	Creative
11. Creativity and imagination is required to make the inferential leaps when analyzing data.	Tr	Creative
12. Science needs creativity and art to construct models, make predictions, compose hypothesis, and devise theories.	Tr	Creative
16. Every scientist has their own prior knowledge, experiences, and bias. Even when studying the same phenomena, scientists will disagree. This is an essential part of science, however, and it would be detrimental to humanity as a whole for scientists to agree on one explanation immediately/completely.	I	Subjective/Theory-laden
21. Theories are evidence based, but they are not set in stone. As new evidence becomes clear, it is more likely that a theory will change.	Tr	Theory/Law
22. Theories are like gladiators. They compete to see which one fits the bill the best.	Tr	Theory/Law
23. A theory is more likely to be modified and fine tuned, rather than disproven or turned on its head.	Tr	Theory/Law
24. Technically speaking a theory cannot change. A theory consists solely of its explanations and connections, and if those explanations and connections are altered then it has produced a new, though closely related, theory.	N	Theory/Law
25. Theories are why" something happens and help us to connect other laws and even other theories."	Tr	Theory/Law
26. Scientists can develop different theories to explain a natural phenomenon based on the same evidence because they interpret the data differently. One theory (that the universe is expanding) is usually better supported than others, but multiple theories can exist at the same time.	I	Theory/Law
27. After scientists have developed a theory, the theory can change.	Tr	Theory/Law
28. Any theory should explain the why of a phenomena to the greatest degree possible supported by the best evidence to that time but should another theory that better comports w the evidence and/or if better/newer evidence comes along, then the theory is subject to change.	I	Theory/Law
29. We bother to teach scientific theories because it demonstrates that science is a tentative, yet durable practice.	Tr	Tentative/Durable
30. Laws are closer to observations/descriptions of what happens in nature under a specific set of conditions. Theories are ideas that attempt to explain how these natural phenomenon happen.	Tr	Theory/Law
31. Laws explain what will happen using some kind of cause and effect relationship while theories attempt to explain why it happens utilizing a grander principle.	N	Theory/Law
32. Scientists used images taken with high-powered technological devices or computational data via scanning and looking at discrepancies in an small area to determine what an atom looks like.	N	Observation/Inference
33. Atoms scaled up look like a bushel of oranges and lemons (protons and neutrons) and then someone took a marble (electron) and threw it ten miles away from the fruit. That would be about what an atom looks like in a large model.	Tr	Observation/Inference
	Tr	Tentative/Durable

Table 7 (continued)

Statement from post-course VNOS responses	Rating	Major NOS element
34. Because tests always yield the same-ish results, we 'know' atoms are made of protons and neutron in the nucleus, and electrons bounce around a fairly confined space in manner that can be reasonable consistent, yet highly erratic.		
35. We are not entirely certain of the appearance of the atom's structure. Scientists are certain of the atom's existence, as well as of the nature of the three particles that make up the atom.	Tr	Tentative/Durable
36. Because we have no way to actually visualize an atom with our own eyes or using tools, our understanding of the shape might change in the future.	Tr	Observation/Inference
37. Scientific knowledge should be based on reproducible, available high quality evidence that is robust enough to stood the test of scientific critique.	Tr	Empirical
38. Science is subjective and has a human element. Additionally, we probably only have a piece of the puzzle, and not all the information. Its like looking at one piece of a 100-piece puzzle and then predicting what the puzzle will look like when it's completed. One prediction could be better" than the other because it encompasses more data.	I	Subjective/Theory-laden
39. Data sets can be huge, nasty, and confusing. Depending on your own point of view and previous experiences, these less than clear-cut data sets can be interpreted in multiple ways, depending on statistical treatments, data selection, etc.	I	Subjective/Theory-laden
40. Data can be interpreted differently, especially when there are large gaps in understanding.	Tr	Subjective/Theory-laden
41. Theory of evolution is an explanation of how organisms change through time. Mendel's Law of independent assortment is a statement of what happens to two different genes, but not WHY it happens.	I	Theory/Law
42. We still teach theories because as it stands, there's no better explanation and with new evidence the theory could very well strengthen to beat up its challengers as showcased in the video.	Tr	Tentative/Durable
43. If grouped differently, evidence can at times seem to point in different directions.	Tr	Subjective/Theory-laden
44. Scientists shouldn't get creative in the presentation of the data, in that we shouldn't manipulate the results (using false precision that seems more valid, or mixing absolute and proportional quantities, etc.). However, if the data show an unexpected result, as a scientist I need to be able to figure if my trials/experiments were faulty, or if the results lead in a completely different direction.	N	Creative
45. There a far fewer laws in biology than in the physical sciences probably because we are trying to impose a rule or human definition upon a natural state of being.	Tr	Theory/Law
46. Data collection requires that scientists adhere to a set of standards (use the same measuring tool, etc). The only time it really requires creativity is when something goes wrong, or when figuring out any trends in data (usually through deciding on what statistical tests should be run).	N	Creative
47. A law is fact and difficult to change. One is the law of gravity. We know for a fact that gravity exists.	N	Theory/Law
48. No creativity during data collection. Process must remain the same all the way through. They can halt collection and begin anew with another creative process. Or.creatively interpret the data.	N	Creative

Ratings are naïve (N), transitional (Tr), and informed (I).

References

Abd-El-Khalick, F. (2014). The evolving landscape related to assessment of nature of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (Vol. II, pp. 621–650). New York: Routledge.

Abd-El-Khalick, F., & Akerson, V. (2009). The influence of metacognitive training on preservice elementary teachers' conceptions of nature of science. *International Journal of Science Education, 31*, 2161–2184.

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*, 417–436.

Aikenhead, G. S., & Ryan, A. G. (1992). The development of a new instrument: "Views on Science-Technology-Society (VOSTS)". *Science Education, 76*, 477–491.

Akerson, V. L., Abd-El-Khalick, F., & Lederman, N. G. (2000). Influence of a reflective explicit activity-based approach on elementary teachers' conceptions of nature of science. *Journal of Research in Science Teaching, 37*, 295–317.

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

Anderson, J. R. (1981). *Cognitive skills and their acquisition*. Hillsdale: Earlbaum.

Bartos, S. A., & Lederman, N. G. (2014). Teachers' knowledge structures for nature of science and scientific inquiry: Conceptions and classroom practice. *Journal of Research in Science Teaching, 51*, 1150–1184.

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.

Clough, M. P. (2007). Teaching the nature of science to secondary and post-secondary students:Questions rather than tenets. *The Pantaneto Forum, 25* Retrieved from www.pantaneto.co.uk/issue25/front25.htm. Accessed 18 Oct 2019.

Cooley, W. W., & Klopfer, L. E. (1961). *TOUS: Test on understanding science (Form W)*. Princeton: Educational Testing Service.

Demirdogen, B., & Uzuntiryaki-Kondakci, E. (2016). Closing the gap between beliefs and practice: Change of preservice chemistry teachers' orientations during a PCK-based NOS course. *Chemistry Education Research and Practice, 17*, 818–841.

Duschl, R., & Grandy, R. (Eds.). (2008). *Teaching scientific inquiry: Recommendations for research and implementation*. Rotterdam: Sense Publishers.

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

Erduran, S. & Dagher, Z. R. (2016). Reconceptualising the nature of science: Why does it matter? *Science & Education, 25*(1), 147–164.

Ford, M., & Forman, E. (2006). Redefining disciplinary learning in classroom contexts. *Review of Research in Education, 30*, 1–32.

Hammer, D., Elby, A., Scherr, R. E., & Redish, E. F. (2005). Resources, framing, and transfer. In J. Mestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective* (pp. 89–120). Greenwich: Information Age Publishing.

Hanneman, R. A., & Riddle, M. (2005). *Introduction to social network methods*. Riverside: University of California, Riverside (published in digital form at http://faculty.ucr.edu/~hanneman/). Accessed 25 Aug 2019.

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 Teacher Education, 90*, 912–935.

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.

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

Kaufman, J. (2006). Card sorting: An inexpensive and practical usability technique. *Intercom, 11*, 17–19.

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.

Knorr-Cetina, K. (1999). *Epistemic Cultures: How the Sciences Make Knowledge*. Cambridge: Harvard University Press.

Kruskal, J. B. (1964). Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. *Psychometrika, 29*(1), 1–27.

Larkin, J. H., McDermott, J., Simon, D. P., & Simon, H. A. (1980). Expert and novice performance in solving physics problems. *Science, 208*, 1335–1342.

Lederman, N. G. (1992). Students' and teachers' conceptions about the nature of science: A review of the research. *Journal of Research in Science Teaching, 29*, 331–359.

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. 831–880). New York: Routledge.

Lederman, N. G., & O'Malley, M. (1990). Students' perceptions of tentativeness in science: Development, use, and sources of change. *Science Education, 74*, 225–239.

Lederman, N. G., Wade, P. D., & Bell, R. L. (1998). Assessing understanding of the nature of science: A historical perspective. In W. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 331–350). Dordrecht: Kluwer Academic.

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*, 497–521.

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

McComas, W. (2019). Principal elements of nature of science: Informing science teaching while dispelling the myths. In W. F. McComas (Ed.), *The nature of science in science instruction-rationales & strategies*. New York: Springer.

McComas, W. F., Lee, C. K., & Sweeney, S. J. (2009). A critical review of current U.S. state science standards with respect to the inclusion of elements of the nature of science. Paper presented at the National Association of Research in Science Teaching, Garden Grove, CA.

Mesci, G., & Schwartz, R. (2017). Changing preservice science teachers' views of nature of science: Why some conceptions may be more easily altered than others. *Research in Science Education, 47*, 329–351.

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.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academy Press.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press.

O'Neill, D., & Polman, J. (2004). Why educate "little scientists"? Examining the potential of practice-based scientific literacy. *Journal of Research in Science Teaching, 41*, 234–266.

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

Osborne, J., Simon, S., Collins, S. (2003b). Attitudes towards science: A review of the literature and its implications. *International Journal of Science Education, 25*(9), 1049–1079.

Ozgelen, S., Hanuscin, D. L., & Yilmaz-Tuzun, O. (2013). Preservice elementary science teachers' connections among aspects of NOS: Toward a consistent, overarching framework. *Journal of Science Teacher Education, 24*, 907–927.

Peters-Burton, E. E. (2015). Outcomes of a self-regulatory curriculum model: Network analysis of middle school students' views of nature of science. *Science & Education, 24*, 855–885.

Peters-Burton, E. E., & Baynard, E. (2013). Network analysis of domains of knowledge about the scientific enterprise: A comparison of scientists, middle school science teachers and 8th grade science students. *International Journal of Science Education, 35*, 2801–2837.

Peters-Burton, E. E., Bergeron, L. & Sondergeld, T. (2017). Re-analysis of epistemic network with NOS family resemblance approach. Paper presented at the European Science Education Research Association, Dublin, Ireland.

Redish, E. (2004). A theoretical framework for physics education research: Modeling student thinking. In E. Redish & M. Vicentini (Eds.), *Proceedings of the Enrico Fermi summer school, course CLVI*. Bologna: Italian Physical Society.

Ryan, A. G., & Aikenhead, G. S. (1992). Students' preconceptions about the epistemology of science. *Science Education, 76*, 559–580.

Smith, M. U., Lederman, N. G., Bell, R. L., McComas, W. F., & Clough, M. P. (1997). How great is the disagreement about the nature of science: A response to Alters. *Journal of Research in Science Teaching, 34*, 1101–1103.

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory* (2nd ed.). Thousand Oaks: SAGE Publications, Inc..

Teddlie, A., & Tashakkori, C. (2009). *Foundations of mixed methods research: Integrating quantitative and qualitative approaches in the social and behavioral sciences*. Thousand Oaks: SAGE Publications, Inc..

Weller, S. C., & Romney, A. K. (1988). *Qualitative research methods: Systematic data collection*. Newbury Park: SAGE Publications, Inc..

Yacoubian, H. A. (2018). Scientific literacy for democratic decision-making. *International Journal of Science Education, 40*(3), 308–327.