www.ijres.net

What Chemistry Students of Differing Ability Levels Learn about NOS within Inaccessible Chemistry Concepts: A Case Study

Mary F. Johnston
Indiana University, USA

Valarie L. Akerson
Indiana University, USA

To cite this article:

Johnston, M.F. & Akerson, V.L. (2025). What chemistry students of differing ability levels learn about NOS within inaccessible chemistry concepts: A case study. *International Journal of Research in Education and Science (IJRES), 11*(1), 1-32. https://doi.org/10.46328/ijres.3572

IJRES International Journal of Research in Education and Science

2025, Vol. 11, No. 1, 1-32 https://doi.org/10.46328/ijres.3572

What Chemistry Students of Differing Ability Levels Learn about NOS within Inaccessible Chemistry Concepts: A Case Study

Mary F. Johnston, Valarie L. Akerson

Article Info

Article History

Received:
22 August 2024
Accepted:
24 December 2024

Keywords

Chemical bonding
Misconceptions
Nature of science
Reaction chemistry

Abstract

This action research case study explored the ability of three high school chemistry students to grow in their understanding of nature of science (NOS) during its explicit-reflective inclusion in two unit chapters on bonding (ionic compounds followed by covalent molecules). Students completed a pre, post and delayed Views of Nature of Science Form B (VNOS-B) questionnaire to measure changes in and retention of science understanding. Prior to viewing the results of classroom assessments or content assessments, students were placed into high, medium and low apparent ability levels based on the results of their pre and post VNOS-B coded results. Additionally, the study explored the mitigation of historical classroom misconceptions in units on bonding and reaction chemistry for these participants and students, in general. Classwork, classroom assessments, laboratory write ups, general cluster group discussions, established instruments (bonding representational inventory and representational systems and chemical reactions diagnostic inventory) and instructor field notes were also included in the case studies. The aforementioned information resulted in recommendations to first introduce NOS with less abstract concepts to enhance the growth in understanding of low-ability students during its inclusion with less accessible chemistry concepts.

Introduction

Nature of science (NOS) is considered a vital part of student development (Lederman, 2007; NSTA, 2020). That is, developing an understanding of NOS may benefit students in five areas which include utilitarian, democratic, cultural and moral aspects of science, as well as deeper learning of science concepts (Driver et al, 1996). Although unanimity has not been established for a definition of NOS, the aspects which characterize how science works have been agreed upon by a consensus of experts in scientific education and science. These characterizations or *aspects* include: tentative nature, observations and inferences, theories and laws, creativity and imagination, partially empirical nature, theory laden nature and sociocultural impact on science. While it may be possible for students to gain understandings of some aspects of science in the absence of explicit discussion (Deng et al., 2011; Dogan & Abd-El-Khalick, 2007; Johnston, 2024), the preponderance of aspects requires both their explicit inclusion within instruction and student reflections on NOS embedded within the content (Akerson et al, 2000). Often, both students and their teachers hold alternative views of NOS. For instance, a frequent alternative view held is the belief in a hierarchy between theories and laws. That is a theory, once proven, becomes a law making a theory inferior to a law; the theory capable of change while the law is unchanging. Educators may also perpetuate the false views of a step-by-step scientific method (Bugingo et al., 2022). Additional misconceptions may include those exemplified by pre-service educators within the field of chemistry, such as the belief that scientific knowledge comes from experimentation and that it is factual, rather than tentative (Ağlarcı et al., 2016). In addition to naïve views of laws and theories, Demirdöğen and Uzuntiryaki-Kondakçı (2016) also describe ongoing misconceptions in observation versus inference with pre-service chemistry teachers.

Hesitancy was also noted in the case of pre-service educators whose belief in the value of NOS did not change despite their experience with the aspects (Demirdöğen & Uzuntiryaki-Kondakçı, 2016). In fact, in-service educators frequently omit NOS aspects from instruction. Often, they simply do not find its inclusion important (Abd-El-Khalick, 1998). The reluctance may also stem from the necessary adjustments in pedagogy (Clough et al., 2010). In their proposed teacher competencies, Nouri et al. (2021) include motivation and belief in the benefit of including NOS as a barrier to pedagogical concerns. In addition, educators may be unaware of NOS in their standards or unclear about its implementation. This may be the case for many classrooms which have included Next Generation Science Standards in its entirety or in part, according to Akerson et al., 2019. The second iteration of NGSS standards has included a version of science aspects in Appendix H (*Understanding the Scientific Enterprise: The Nature of Science in the NGSS)* which were extrapolated from the cross-cutting concepts and science and engineering practices (Lead States, 2013b).

Despite the inclusion of NOS within Appendix H, NOS is both underrepresented and underutilized within high school science classrooms (Johnston, 2024; McComas & Nouri, 2016). Presumably due to a lack of training in and awareness of both the Appendix H and its application (Akerson et al). McComas (2016) described NOS within NGSS as a hidden dimension of the framework. Within lead states such as New Jersey, where the action research took place, educators were presented with NGSS in 2015. NGSS are our state science standards, and training initially emphasized implementation of the three dimensional framework. NOS has recently been included in training, with similar to the reluctance to its inclusion. For instance, during a recent American Chemical Society conference, the high school chemistry educators with whom the first author spoke were each unfamiliar with NOS and during training sessions, a hesitancy to add NOS to the delivered curricula was noted (Johnston, 2023).

Lederman (2007) suggested that NOS may enhance student understanding of science concepts, while emphasizing a lack of empirical evidence. Despite the lack of sufficient empirical evidence, researchers (*e.g.*, Clough et al, 2010; Johnston & Lane, 2022; Peters, 2012) agree there is a correlation between NOS comprehension and content comprehension. The author also cautions that the inclusion of contextualized NOS within abstract science concepts may interfere with student learning or growth in NOS understanding. Therefore, the ability to embed NOS within secondary science classrooms which are foundationally abstract may be beneficial, yet a question remains regarding efficacy.

High school students often find chemistry challenging. Chemistry is an example of a secondary science classroom which is foundationally abstract. Here, the use of the term *abstract* indicates concepts which are not readily accessible to learners (Michel & Neumann, 2016). Nakhleh (1992) suggests learning chemistry may be difficult for students who hold misconceptions, such as models of matter that include bonding, an abstract concept. However, alternative misconceptions may vary representationally. That is, students who can comprehend or discuss concepts at the macroscopic levels may fail to correctly discuss the same concepts at the symbolic or submicroscopic level (Majeed et al., 2023; Taber, 2013). The use of multiple levels of representation during instruction is common practice within the primary author's classroom and was included in both parts of the action research study. The goal is for students to arrive at an ability to achieve representational competence, or the ability to readily shift between levels (Naah & sanger, 2012).

Regardless of the representational level, alternative understandings often resist instructional remediation and their persistence impedes learning subsequent content ((Luxford & Bretz, 2014; Boo &Watson, 2001; Kind, 2004; Tsaparlis et al., 2018). Bowe et al (2022) provide one example of a misconception in chemistry at the submicroscopic level. The authors describe the conflation of ionic and covalent models when identifying substances such as $CaCl_2$ as covalent. This alternative understanding may be perpetuated into units on reactions where students need to consider not only the patterns of various reactions, but also how bonds are breaking and forming within these systems (Ralph et al., 2022). The unit on reactions may be considered more accessible than bonding due to the ability to observe indicators such as color changes, formation of precipitates, formation of bubbles or creation of light or heat. However, when predicting products or writing the symbolic chemical equations, students are asked to not only include the ionic or covalently bound compounds and molecules, they are asked to change the reactants, break bonds or create bonds to form products within correct reaction types (Boo & Watson, 2001; Naah & sanger, 2012; Surif et al, 2018; Taber, 2018; Yitbarek, 2011). Knowing why the reaction is occurring (Boo & Watson, 2001) or that it is not occurring simply to form an octet (Taber, 2019); understanding that the ionic compounds are not reacting with water (Naah & Sanger, 2012), and understanding how to reflect the correct symbolic representations of products (formula units or molecules) including coefficients or subscripts (Yitbarek, 2011; Surif et al, 2018) are each commonly misunderstood and stem from alternative understanding within bonding,

As has been discussed, ambiguity exists regarding the efficacy of introducing NOS within more abstract science concepts (Lederman, 2007). The purposes of the action research were to determine how chemistry students who have received no prior instruction in NOS aspects grew in their understanding of both aspects and content during units which are foundational and inaccessible in chemistry. In addition to the explicit-reflective NOS strategies included with inaccessible chemistry concepts and impacts on misconceptions during these units, the second action included the subsequent chapter on reactions in the absence of contextualized NOS.
In the action research study, the following question was considered

1. How do students of differing ability levels conceptualize NOS and abstract chemistry concepts within explicit and reflective instruction?

Conceptual Framework

NOS has most effectively been embedded within K-12 classrooms in an explicit-reflective manner (Akerson et al, 2000; Ağlarcı et al., 2016; Akerson & Hanuscin, 2007; Akerson et al., 2014; Akerson et al., 2019; Dogan & Abd-El-Khalick, 2008; Johnston & Akerson, 2022; Torres & Vasconcelos, 2019; Wahbeh & Abd-El-Khalick, 2014). Therefore, this action research study employed explicit-reflective embedding of NOS within the chapters on ionic compounds and covalent molecules; followed by an introductory unit chapter on reactions in the absence of contextualized NOS. The setting of the action research was within an NGSS chemistry classroom with established cluster groups of three students, and which also included multiple levels of representation (Johnstone, 1982), as has been the established pedagogy within the classroom. The multiple levels include macroscopic, symbolic, and submicroscopic representations of concepts.

Nature of Science

Historically, science and how it works has been considered an important part of student formation in sciences. Experts such as Contant (1951) did not consider merely *knowing* scientific concepts to be sufficient for students to develop appropriate understanding of science. This ongoing belief has been propagated by educational researchers over time and is discussed within the introduction to NOS in Appendix H (Lead States, 2013b). The necessity for educators to comprehend NOS (Lederman, 1992) replaced prior assumptions that students would grow in NOS comprehension without adjusting pedagogical practices or instructor training. However, the author described a need for training in the transmission of NOS within the classroom in his review (Lederman, 2007).

Initial adjustments were made for including NOS within science classrooms. The initial *implicit* inclusion of NOS, or without a discussion of how the concepts being studied related to NOS depended on a natural improvement in comprehension following inquiry-based instruction. Khishfe and Abd-El-Khalick (2002) citing Durkee (1974) explain this implicit strategy of NOS "…assimilated via a kind of osmotic process during science activities." (p.352) as ineffective. The *explicit* inclusion of NOS within science classrooms was preferable. Making clear connections between NOS and the particular content being learned, as well as connections between students within the laboratory and their connection to how science works was preferable. However, it is also important to allow students to reflect on the NOS aspects. The embedding of the aspects in an explicit-reflective manner has been shown as the most efficient strategy (Akerson et al, 2000). Part one of the action research followed this gold standard in NOS instruction.

An instrument has been developed which measures students' views of nature of science (VNOS). This benchmark test was developed to determine NOS comprehension, and construct validity has been established. While previous instruments limited test takers to selective item responses, VNOS utilize an open ended questionnaire (Lederman et al., 2002). Multiple forms of VNOS have been developed (*e.g.,* A, B, C, D, D^+ and E). The initial form (VNOS-A) was developed by Lederman and O'Malley (1990). Subsequently, Abd-El-Khalick et al. (1998) adjusted this questionnaire to include additional questions. The updated form (VNOS-B) suggests a semi-structured interview for 15 – 20% of participants (Lederman et al).

The VNOS-B has been utilized by most pre-service and in-service educators, as well as each of the secondary school research studies cited within this publication. A more complex questionnaire has been developed (VNOS-

C) which is most often utilized by scientists (Ariyarante, 2023; Ayella-Villamil & Garcia-Martinez. 2020). The VNOS-E is a form which was created for use with younger students (K-3) and would not be appropriate for secondary school students (Lederman, 2007; Lederman et al., 2014). The action research study described in this publication utilized the six-question version of the VNOS-B instrument, as suggested by Ayella-Villmil and Garcia-Martinez. The use of the VNOS-B questionnaire was grade level appropriate and allowed students to expound on the questions posed in an open ended manner.

Chemistry

As previously outlined, the abstract nature of chemistry is frequently the cause of ongoing alternative understandings of the content. The inaccessible concepts within chemistry are often the foundational concepts in multiple units of the course. Over the past several years, the NGSS Framework or a derivative thereof has been implemented within many classrooms (Judson, 2022). The classrooms in which the action research took place utilized the three-dimensional framework. In addition, Johnstone's (1982) three levels of representations are a constant with the instructors' classroom. The classroom itself is organized by cluster groups of students (generally 3 students). When forming the cluster groups, there is a consideration of both potential academic abilities as well as socio-emotional interactions. Often, students are able to select their groups and conflicts are resolved or students are permitted to request temporary changes with groups. During the action, students had an established routine and expectation when working within cluster groups.

Units on bonding included reflections on NOS to which students initially responding independently. Cluster groups were comprised of students familiar and comfortable with one another allowing productive discussion and self-correction following the independent reflection. Students were also able to make adjustments as we reviewed the reflections in a whole class environment. During the unit on reactions, students continued to work within their cluster groups, following the same pedagogy in the absence of NOS reflections.

To measure growth in student understanding of bonding, a bonding representative inventory (BRI) was incorporated. This inventory was developed by Luxford (2013) with reliability and apparent validity described (Luxford & Bretz, 2014). It is notable that the validity for HS level students did not include interviews on item syntax. This instrument was developed for use with undergraduate, advanced placement and high school level chemistry students. The author describes Cronbach α scores as indicators that students continue to grow in their comprehension of bonding over time. The inventory was developed to identify misconceptions at different levels of representation (macroscopic, symbolic and submicroscopic) and may be used as a tier-1 or tier-2 instrument. In addition to the BRI, students completed a classroom assessment for which a review of reliability has not been assessed. However, items are similar to historic classroom assessments and results are included in field notes.

To measure student growth in reaction chemistry, the representational systems and chemical reactions diagnostic instrument, (RSCRDI) was selected (Chandrasegaran, 2004a). This diagnostic instrument was developed (Chandrasegaran, 2004b) to identify student misconceptions in chemistry at different levels of representation. The instrument was assessed for reliability and apparent validity (Chandrasegaran et al., 2007). The instrument was created for high school level students, after they had completed their chemistry course, with both control and treatment having observed each of the items during hands on laboratories, with the difference being the emphasis on levels of representation. This action research included slightly less than three weeks of the introduction to reactions, and items were not observed within the laboratory. However, the items which were relevant did inform apparent growth. In addition to the RSCRDI, a classroom assessment on reactions was administered.

Method

In this section the methodology and the case study will be explained. In the course of responding to the research question the participants were leveled following the post and delayed VNOS-B questionnaire coded responses. The levels consisted of apparent high achieving students who held at least three informed views of science and no inadequate views, apparent medium ability was reflected in students who responded with at least two informed and no inadequate views, those students who arrived at only one or fewer informed views and held multiple inadequate views in their pre-interventional VNOS-B were placed within the low achieving level. Three students were selected for the case studies. Their selection criteria included views of nature of science questionnaires which did not require significant clarification and being a clear representative of the level were selected. A student who was at the cusp of a level, or whose responses were unclear would not be selected. The responses on their content assessments were not included in either their selection or their apparent ability levels.

Context

The action research took place in college preparatory chemistry classrooms of the first author. The high school is situated in a rural New Jersey town. These classrooms are predominantly 11th grade students in a non-elective chemistry course. In addition to college preparatory classes, the high school offers small group (SCP) classes, conceptual chemistry, honors level and advanced placement chemistry. Students taking college preparatory chemistry are not generally interested in continuing in their studies of chemistry nor do they meet the prerequisites for advanced placement chemistry during their high school tenure. Therefore, this is often the final science class in post-secondary classrooms, unless a science elective is taken.

In this publication, three students have been selected for case studies. Three of the students selected were participants reflecting apparent low, medium and high achievement levels; and experienced the design during face-to-face instruction with the first author. "*Samantha*", the low-achieving student was one of the most focused and detail-oriented students in the study. Her work ethic and participation were stellar, as was her attendance. The medium-achieving participant, "*Rebecca*," is an outgoing and motivated student whose note taking and participation was quite similar to that of Samantha's, yet her attendance was at times interrupted by absences from school or during participation in school based event (field trips or peer based). Finally, "*James*" was selected as the high-achieving student. On par with both Samantha and Rebecca, James was also quite adept and focused on both notes and participations. He is an outgoing young man and interested in future studies in science. His attendance was similar to that of Rebecca, the two made every effort to inform their instructor in advance and make up work in a timely manner. The leveling of these participants was based solely on their VNOS-B questionnaires and NOS comprehension. The interventions included the introduction of NOS without the inclusion of chemistry concepts (decontextualized), followed by the introduction of both ionic and covalent bonding with the inclusion of explicit-reflective NOS (contextualized). Following this first part of the action, an introductory unit on reactions was presented in the absence of contextualized NOS.

Action

Although NOS is usually introduced during the first chapter unit on scientific process, the presentation of NOS aspects in the absence of chemistry content or *decontextualized* instruction of NOS aspects was not presented to students until the first week of the action research. Preferably, students would receive multiple iterations of NOS earlier in their chemistry classroom, as it is suggested that students are first introduced to decontextualized NOS followed by contextualized NOS; cycling through each throughout the academic year (Clough,2006). Due to pending high stakes assessments, the decontextualized NOS was presented with fewer activities and discussions than may be preferable as an introduction. Students received two handouts during this initial NOS instruction. The first was a modified Appendix H handout with grade level exemplars of NOS derived from science and engineering practices, as well as cross-cutting concepts (Lead States, 2013b). The second handout was a blank list of science aspects onto which students could take notes in their own words. Both handouts were available to students during the contextualized reflections portion of the action research. Prior to the lessons which introduced decontextualized NOS, a pre-interventional VNOS-B questionnaire and pre-interventional BRI were completed.

Once students had been introduced to NOS aspects or characterizations, they were ready to reflect on NOS embedded within their chemistry content. This *contextualized* presentation of NOS was presented in an explicit-reflective manner. Here students responded to reflection questions first independently, then in cluster groups and finally reviewed as a whole class. For example, one set of reflections questions following a laboratory included "*How is this laboratory similar to the work conducted by scientists? How is it different? Select and explain two NOS aspects which describe your response"; "Did prior experience provide a hint about what you might observe? How does this relate to NOS aspects?"* Following part one of the action research, a classroom assessment, a post BRI, and a post VNOS-B questionnaire were completed.

Units on Bonding

The contextualized NOS portion of the action research study included two chapter units on bonding. Prior to the beginning of this section, a pre-interventional RSCRDI was presented. The first unit was on ionic compounds and the second unit discussed covalent molecules. Each unit included a set of reflection questions. That is, during the unit on ionic compounds, students responded to three sets of NOS reflection questions and during the unit on covalent molecules students also responded to three sets of NOS reflection questions. The students also completed study guides, practice with creating and naming various compounds, laboratory experiments, and classroom assessments. A more detailed outline of the sequence is presented in Table 1, which described the concept, lesson and timing within the action. A more detailed description may be found in Johnston (2024).

Table 1. Overview of Action for Part One (Ionic and Covalent Bonding)

Week	Concept	Lesson
One Dec 22-24 *Two days	*Pre-VNOS B* *Pre-BRI*	Independent assessments (VNOS-B and BRI) given over two days, or during lab.
Two Jan 3-5 *Three days	*Pre-RSCRDI* NOS and Appendix H Practice	Pre-RSCRDI and Introduction to Modified Appendix H and NOS handouts. Decontextualized NOS aspects; defined and rephrased. Tube Activity (modified) connected to NOS
Three Jan 8-12 *Four days	Conductivity Demonstration Conduction prompts (1-5). Review reflections from prompt 1.1 (1- 5) Ionic compound, crystal lattice, formula unit, electrolyte and conduction. Provide common misconceptions 1 and 2. Reflections for 1.2 prompt: Diagram and NOS Review reflections. Polyatomic ions and nomenclature. Provide common misconception 3. Properties Laboratory, obtain data.	Demonstration (conductivity) and first reading History of electrolytes (Faraday and Arrhenius on electrolytes with reflection questions; *Tentative Nature; Theory vs Law).* Review reflections 1-5 as a whole class. Introduce Crystalline Lattice: Formula Units of Binary Ionic Compound NaCl, CaF_2 and AlP); Conduction and Electrolytes. Begin practice. Begin second prompt reflections. Complete / Review reflection on crystalline lattice (1 - 2 *Theory versus Law*; *Observation v Inference*). Whole class review diagram; discuss inferences v observations in demonstration. Practice creating and naming formula units. Obtain data (properties lab). Reflections and analysis to follow with formal write up.
Four Jan 15-19 *Two days (Snow days)	Properties lab reflections (1.3); NOS aspects Formula Units practice Create formula units (Binary Main group and Transition; Polyatomic ionic compounds) Check for comprehension. C.E.R to identify unknown	Properties laboratory reflections completed. Review reflections (*Myth of scientific method; Creativity and imagination; Human endeavor*). Brief practice; Properties Laboratory Analysis questions. Properties Laboratory – Analysis questions and write up [C.E.R. includes

Week	Concept	Lesson
	substances A – E; formal write up.	identities of substances A,B,C,D & E; bond types, formula units and diagrams]
Jan 22-26 Mid-Term Schedule **One Day	Midterm Review [all concepts to this point] Midterm Complete ongoing practice; reinforce polyatomic ions in ionic compounds. Or complete write up.	Review for midterm (class) Midterm exam (Two block periods) Complete write up and part of practice (as needed)
Five Jan 29 –Feb 2 Make up for snow days this week.	Review prior reflections (reinforce contextualized NOS). Reinforce formula units (transition and polyatomic). Begin second set of reflections 2.1; NOS Reinforce transition metal with polyatomic ion [$Cu(CO_3)$]. Proust Nomenclature, identifying and diagram covalent versus ionic. Single Double Triple; Diatomic Molecules Lewis (history) reflections 2.2. Lewis and Structural Formulas.	Review reflections and notes from Ionic Bonding; Complete previous practice and review polyatomic (content missed on snow day). Proust prompts and reflections (2.1) with images of and calculation students reference $Cu(CO_3)$ while calculating H_2O). *Theory versus Law; Observation v Inference; Tentative nature* Covalent nomenclature onto study guide. Practice with nomenclature, identification and diagram. Complete practice (WS Covalent 1); Single, double and triple bonds into study guide; Discuss Lewis and Langmuir respond to Reflection Question 2.1 (*Creativity and Imagination; present findings; Ethics)* Ionic versus Covalent *(*Lewis structures) Lewis Structures. Transcribe Lewis and Structural formulas (use virtual program: PHET) Complete reflections 2.2; review 2.1 and 2.2. Add notes on 2.2 to study guide.
February Six Feb 5-9	Brief description polarity (partial charges H_2O); ABE system introduced.	Observe calculation for polarity and bond type; Begin reflection 2.3 (Sedgewick/Powell; Gillespie/ Nylhom) *Tentative nature; Theory versus Law;*

Week	Concept	Lesson
Half Day 6 Feb Half Day 8 Feb	Review 2.2, Begin 2.3	*Creativity and Imagination (technique)* Shapes (ABE System). WS2 practice started as students who need to complete independent reflection (R 2.2) get caught up.
3.5 or 2.5 days.	VSEPR reflections here Molecular Shapes completed; using ABE system create models of various molecules.	Delayed opening: Discuss reflections (correct misconceptions; use PHET to show lone pair repelling branches); Begin Molecular Models Lab
	Day Two of Model Laboratory. Extra practice with formulas and naming; structures.	Review work (Lewis and Formula structures) constructed (Models). Review Reflections (*Creativity and imagination; Theory versus Law, Observation versus Inference*)
	Review and extra practice	Extra practice with nomenclature and identifying types of structures / bonding. Review bonding (ionic and covalent)
Seven February 12-16	VNOS-B and quick review concepts.	Quick review for quiz. Post VNOS-B
Snow Day 2 or 3 days	Snow Day Assessments BRI and Quiz	Snow Day Bonding quiz with Post-BRI

Note: From Johnston (2024)

In this part of the action research study, students were presented with the introductory chapter on reactions in the absence of explicit-reflective NOS. This part of the action was included, as suggested by Lederman (2007) where more abstract concepts should follow less abstract or inaccessible concepts without the embedded NOS. The students completed a study guide, practice such as creating and identifying reaction products, multiple laboratory activities and a classroom assessment. At the time of the classroom assessment on reactions, students completed their post RSCRDI. In addition, students completed the delayed VNOS-B questionnaire and the semi-structured interview was conducted.

Reaction Chemistry

The introductory unit on reactions for college preparatory students establishes a foundation for subsequent chapters on stoichiometry and acid/base chemistry. The chapter includes an explanation of reaction indicators, and the correct use of the term “reaction”, equation types, reaction types, balancing (conservation of mass), creating word equations and predicting products of single and double replacement (displacement) reactions. The lessons were presented similarly to those in the previous units on bonding, with the exception of contextualized NOS. Student cluster groups were not adjusted, unless requested by students. A brief summary of concepts and lessons has been included. A more detailed explanation may be found in Johnston (2024).

Table 2. Overview of Action (Simple Reaction Chemistry)

Week	Concept	Lesson
Seven February 15-16 Snow Day End of week	Begin RXN w/ demos (two solutions) *Magnesium Lab Data* *Demos*	Demonstration (with aluminum) to be shown next over time. Complete magnesium activity
Eight February 19-23 Three Days	Magnesium analysis and introduce reactions (basic vocabulary). Indicators, parts of equation, reaction and equation types Synthesis, Decomposition and Combustion reactions. Word equation for what we have discussed in previous classes and begin SR reaction (steps to predict product and step to balance). Introduce activity series. Begin RXN lab one (obtain data and begin first reaction).	-Determine percent magnesium or oxygen and error (experimental versus theoretical). -Notes on parts of equation and pertinent vocabulary (coefficient, subscript). Identify reaction types; Identify equation types. Notes and patterns for synthesis, decomposition and combustion reactions. Students add the product to word equations. Show before and after images and the pattern for SR RXN, record and use steps as whole class to balance, use activity series (aluminum above copper) and create simple diagram. Predict the products and indicate if reactions occur (activity series). Obtain data for SR RXNs, determine if predicted correctly.
Nine Feb 26-29	SR RXN analysis (write the reactions and word equations); one diagram. Introduce DR RXN (with demo); solubility chart. DR reactions activity (DR RXN lab)	Complete write up (balance reactions) and create one diagram (choice). Whole class review. Silver nitrate and magnesium chloride (or similar) demo. Pattern for DR RXN and Solubility chart, if reactions occurs. Predict reactions which occur then conduct obtain data. Analysis includes balanced

Week	Concept	Lesson
		equations and choice of one diagram.
	Reactions 2 write up and begin extra practice. Practice with equations and reaction types. Go over diagram and missing notes.	Complete write up (balance equations) and whole class review. Extra practice is completed while students check in.
March Ten	Complete extra practice and review as a whole class.	Review practice as a whole class, white boards today or next day.
Mar 4-8	Review for quiz on reactions.	Kahoot.it game for students. White boards.
** Continue to next week as needed.	Class assessment and RSCRDI	Classroom assessment and include RSCRDI.
NJGPA infrastructure this week.	*POST RSCRDI* *Delayed VNOS - B*	Delayed VNOS-B and RSCRDI
Mar 11 – 15 *NJGPA testing 11 and 13*	Complete classroom assessment, error analysis, make up assessments (reactions and / or VNOS-B).	Error analysis, science questions or make up assessments will be administered this week.
PD Session, Delayed opening 12th	Semi-Structured interview this week.** March 27	

Note. From Johnston (2024)

Data Collection

Data were collected from the previously described instruments, classroom practice, laboratory write ups, written reflections, classroom assessments and instructor field notes. The instruments and classroom assessments were maintained by gatekeepers to ensure anonymity and confidentiality. Formative work and student reflections were maintained by the first author. Field notes were either written in an instructor journal or transcribed from daily audio reflections. Field notes also included paraphrased student discussions and observations from student reflections or practice (independent and cluster group work).

The VNOS-B instrument was selected to measure student understanding of NOS concepts. The pre VNOS-B was administered in December, the post VNOS-B was administered in February and the delayed VNOS-B was administered in March. Finally, a semi-structured interview was recorded in April. To provide a small formative assessment grade, the post and delayed VNOS-B questionnaires were reviewed briefly prior to being submitted to gatekeepers. The VNOS-B which were returned following the action research were rated using previously established coded (discussed in the next section).

The instrument which was selected to measure student understanding of ionic compounds and covalent molecules at differing levels was the BR which was introduced by Luxford (2013). This selective response assessment was presented to students prior to their decontextualized NOS intervention (December) and following the two chapter units on bonding (February). All items were presented to students, yet not all items were included in analysis, as not all items reflect the college preparatory chemistry curriculum. The BRI is an instrument which may be reviewed as either a 1-tier or 2-tier diagnostic (Luxford & Bretz, 2014). The classroom assessment on bonding was administered in tandem with the post interventional BRI, on the same day.

The instrument which was selected to measure student understanding of reaction chemistry (RSCRDI) was developed by Chandrasegaran (2004a) and permission to use the instrument, as well as the item key was provided by Dr. David Treagust. The instrument is a 2-tier inventory which may also be used as a 1-tier. The post interventional RSCRDI was presented to students in tandem with the classroom assessment on reactions. The classroom assessment did not undergo a review for reliability, yet items reflected historical questions and misconceptions.

Data Analysis

Student understanding of NOS was analyzed first by a quick review of post interventional and delayed VNOS-B questionnaires as part of a small classroom grade, prior to submitting them to gatekeepers. At the end of the action research, the questionnaires were returned without either student or version identifiers. The blind coded questionnaires were then coded by the primary author utilizing previously established codes (Akerson et al, 2019) for inadequate, adequate and informed responses. In addition, students approaching adequate or informed were delineated. The coded responses were then sent to the second author, an expert in coding NOS responses, to establish inter-coder reliability. Following the adjustment of a single response, 100 % inter coder reliability was established (O'Connor, C., & Joffe, H. (2020). The data was then utilized to place student participants into apparent ability levels.

The selective response key provided by Dr. Bretz was utilized when reviewing the BRI. This instrument is designed to identify misconceptions in bonding at various levels of representation and is intended for high school chemistry, advanced placement chemistry and undergraduate chemistry students (Luxford & Bretz, 2014). As a number of items on the assessment were beyond the scope of the curriculum, some items were either referred to as *unexpected*. The pre interventional and post interventional BRI was presented to students with both a hard copy of the instrument and a Scantron®. The Scantron® was utilized to arrive at a small score for students. This score reflected the *expected* items only. Once scores were recorded in instructor gradebook, names were cut from the Scantron® and it was stapled to the hard copy. Both were then presented to the gatekeepers until data was returned for analysis in the absence of student identifiers which had been replaced by numerical identifiers.

The key for selective responses for the RSCRDI was used to analyze student progress in reaction chemistry. In the case of the RSCRDI, not all items were presented to students. Of the items presented, those which reflected curricular content were identified (*expected*), as were those which students may have been able to answer (*possible*) and those which were beyond the curriculum (*unexpected*). Similar to the BRI, the assessment was presented with both a hard copy and a the Scantron®, which was utilized to score the assessment. The score reflected the expected items. The post – RSCRDI was presented at the time of the classroom assessment on reactions. Once scores were recorded, a similar process of submission to the gatekeepers was followed. Both were returned to the primary author for analysis in the absence of student identifiers, which had been replaced by numerical identifiers.

Field notes included the data recorded while observing student interactions, listening to group reflections, notes about how students responded to questions posed or errors made or avoided on practice, reflections or laboratory write ups or a summative project. In addition, the classroom assessments were described either in instructor notes or daily recorded reflections. The instructor notes and recorded reflections which had been transcribed were reviewed for themes or for statements regarding student growth or misconceptions. These comments or notes on progress became part of the data, as able.

Results

Nature of Science

The first part of the action research study assessed student ability and growth in NOS comprehension, bonding comprehension and possible mitigation of historical misconceptions. In this section, general results are presented. Following a discussion of the second part of the action, a more detailed discussion of three student participant case studies is presented.

Pre, Post and Delayed VNOS-B

Field notes suggested that students held predominantly inadequate views of aspects such as theory and law and scientific process. A review of post and delayed VNOS-B questionnaires suggested growth toward adequate or informed following contextualized NOS embedded within two units on bonding. The coded responses which were reviewed by the second author reflected improvement to at least approaching adequate for all aspects with the exception of observation and inference for students in the apparent low achievement level, with improvement to at adequate or approaching adequate for the same aspect in the delayed VNOS-B. The most growth was observed was observed when describing the tentative nature of science, creativity and imagination (myth of scientific method) in the post VNOS-B, with no inadequate responses. Field notes suggested additional growth overall.

Leveling of Participants

While reviewing the post VNOS-B, it appeared that a natural leveling of students had occurred. Students who had at least three informed views of NOS and who had no uninformed or inadequate views of NOS were placed into an apparent high achieving level, students who were informed with at least two NOS aspects and no inadequate views in their post or delayed VNOS questionnaires were considered medium ability level and finally the students whose responses were limited to one or less informed views of NOS, and who may have ongoing inadequate views or who had multiple inadequate views in their pre- assessment were considered to be low achieving students.

Bonding

Prior to their summative assessments, students completed study guides, practice with formula units, properties activity, practice with diagrams, and a formal write up of the properties activity during which they identified each of five unknown substances based on their properties. The students completed a BRI prior to and following their chapters on bonding. The students also completed a summative classroom assessment on bonding.

Pre and Post BRI

In general students demonstrated growth over on the post BRI assessment from the pre-BRI, field notes indicated that the tier-1 general results reflected growth (10.24 ±3.14). Expected items included #'s 1-2,7-8,11-12,14-15 and 17 – 23.

It appears that students outperformed when identifying the symbolic level covalent molecule in the first item, the shared electrons and nonmetals involved in items twenty and twenty-one; identifying the covalent versus ionic lattice in item seven; and submicroscopic explanation of ionic lattices in item twenty-three.

Classroom Assessment

In general students demonstrated an improved ability to respond to questions on bonding. The ability to achieve proficiency with concepts at the submicroscopic level may reflect movement toward representational competence. Field notes suggested that students had improved on historical results when diagramming systems of simply binary ionic and covalent molecules in solution. Field notes reflected a 100 % ability to separate binary ionic compounds in solution and 17% of students separated the covalent molecules. The addition of a more complex ionic compound which included both a transition metal and polyatomic ion in the current assessment fared better than previous iterations of simple binary ionic compounds, with 15 % leaving the complex compound together, and 17 % separating the polyatomic ions in solution. Improvements were also noted in the ability to create formula units and describe both ionic and covalent molecules.

Reactions

As previously described, students received instruction on introductory reaction chemistry in the absence of contextualized NOS. The students completed a study guide, three laboratory activities and reaction practice before completing their summative assessments. The students completed a RSCRDI prior to and following their chapters on bonding. The students also completed a summative classroom assessment on bonding.

Pre and Post RSCRDI

In general students demonstrated growth from their pre RSCRDI. The student participant responses were checked on both the Scantron® and the printed assessment; pre-RSCRDI 1-tier of 7.8 ± 2.12 and 2-tier mean of assessed items of 1.8± 0.71 for the 11 assessed two part items. The post-RSCRDI results show a mean tier-1 of 11. 8 ± 4.05 and a tier-2 of 4.46 ± 2.6 for the 11 items selected. Field notes indicated a slightly lower 1-tier of 10.6 ± 3.33. Some students responded to items which were intended to be references, shifting some responses. Therefore, general results may be inaccurate. However, the students grew in expected, as well as "*possible*" and in some cases "*unexpected*" items. The items presented to students included #'s 1-6 and 10-15. Item #12 was a reference item and not intended to be assessed.

Of the items, one or both parts of item #'s 1,2, 4, bottom of 14, and 15 included concepts which were either part of instruction or concepts which could be inferred based on instruction; item #'s 3, 10 and 13 were not part of the discussion and were not expected, yet considered possible and finally, item #'s 5, 6 and 11 were included yet correct responses were unexpected. Again, levels of representation did not appear to be as significant to correct responses as the concepts found within the items. In fact, the most growth was found in item #10 with both parts at 100% correct.

This item included each of the three levels of representation. Item #3 reflects submicroscopic and symbolic levels and both parts were correct at 80 %. A similar finding for the least growth was observed in item # 11, which also included all three levels of representation for both parts (macroscopic; submicroscopic/symbolic). Expected items #1 and 2, constituent atoms and the synthesis reaction of magnesium in diatomic oxygen were at 40%, The single displacement reactions forming diatomic hydrogen, in expected item #4 was 60%. Expected item # 15, a single displacement reaction in which the less reactive cation formed a solid metal was 60%. Possible item #3, an acid base reaction with no symbolic equation provided, was 80%, while possible item #10, was 100% correct.

Classroom Assessment

The classroom assessment, and in particular the final three-part open ended item was encouraging. All students demonstrated the ability to create appropriate products in their chemical equation as well as the word equation. The three-part item was based on that of (Nyachwaya et al., 2011), however it did not include a selective response. The item was also incorporated previously in the primary author's classroom.

In general, field notes indicated 11.6 % of students transcribed subscripts, 6.9 % included the elemental rather than constituent atom of the metal in solution, 4.6 % did not complete balancing and 2.3 % split the formula unit rather than placing a coefficient before the compound when balancing the equation. No students combined the complex ionic compound in solution nor did they separate the polyatomic ionic ($PO_4{}^{3-}$). No students had an incorrect word equation, however one did not have time to complete this question. Finally, no students followed an incorrect method to predict the product or if the reaction occurred. The item demonstrated increased errors at the submicroscopic level, with slightly fewer at the symbolic level.

Case Studies

The three students who have been selected for a more detailed case study are those who reflect high, medium and low- ability levels. As previously described, the students were placed within levels solely based on their post-interventional and delayed-interventional VNOS-B questionnaire coded responses.

Apparent Low Achieving Student "Samantha"

When reviewing the VNOS-B, Samantha moved from being adequate in tentative nature of science and sociocultural aspect, and inadequate for the remaining aspects (inference versus observation, theory versus law, creativity and imagination, myth of scientific method) to approaching informed for the tentative nature of science, myth of scientific method and sociocultural aspects; approaching adequate for inference versus observation, theory versus law and creativity and imagination, in the post-interventional VNOS-B. Her delayed VNOS-B showed growth to informed for the tentative nature of science; she remained at approaching adequate for inference versus observation and approaching informed for sociocultural aspect; and she moved back toward pre-interventional views with theory versus law and creativity and imagination falling to inadequate.

While Samantha was able to continue growing toward informed responses to the tentative nature of science as it applied to theories on the delayed VNOS-B:

> "Yes, after a scientist has developed a theory examples being atomic theory, kinetic molecular theory or cell theory it can change. *Even though a scientist took the time to develop and research a theory it can always be altered to improve it."*

Her response regarding theories and laws became more succinct:

> "Yes I would say that there is a difference between a scientific theory and scientific law. I think this is because a theory is based on observation/ experimentation while a law is based upon hard facts (research). All theories can later be turned into laws." Samantha left out the earlier statement that laws and theories are both of equal importance.

When responding to independent and then group reflections on bonding, Samantha struggled with similar aspects. For instance, when asked "*In the third reading, Arrhenius describes a delay in publishing his work. What caused the delay? In your opinion, was this a dissociation theory or a dissociation law? Explain your response."* Samantha initially felt the dissociation of electrolytes was a law

> "…because he based his descriptions off facts" and then adjusted during whole class review to "Theory not a law because a theory is more inferential".

By the second unit on bonding Samantha was able to describe that both theories and laws can change, citing technology as an example of what may allow this and tentative nature of science as an aspect which reflects the change.

When reviewing the BRI, Samantha was the lowest scoring student. In fact, Samantha's post BRI scores were below the mean reported 1-tier and 2-tier from the literature. She was able to respond correctly to expected items 1, 3, 16, 19, 20 and 21. Although Samantha responded incorrectly to item #2, her response was an expected error, demonstrating more a lack of understanding of electronegativity rather than bonding (Luxford, 2013).

The classroom assessment on bonding included a few items which were comparable to historical items. Here, the item which was reviewed included the system for overall field notes and comparing to previous results. Here. Samantha demonstrated one of the lowest scores. However, she was able to diagram her binary ionic compound with the correct charges and separation for the $MgCl_2$. She was also able to leave the covalent molecule together. Her error was limited to confusion about how to diagram the complex ionic compound in water. While she correctly separated the carbonate from the copper, she also separated the covalently bound carbon and oxygen of the carbonate. This error was only observed in a small percentage of students, generally.

Finally, when considering the RSCRDI Samantha struggled more than the remainder of her peers. Once again, her effort was apparent and the errors that she made reflected alternative understanding. Her responses were mostly incorrect, with 4 total parts correct and only 1 item correct in both parts. Errors consisted of using single displacement resources to respond to double displacement items, and vice versa.

The classroom assessment on reactions was also challenging for Samantha. However, her diligence was evident in numerous notes to self which were written on her assessment. She also took the time to write the pattern and type of reaction on top of her work "double replacement" as well as the pattern to follow "$AB + CD \rightarrow AD + CB$". She made a mistake with her equation not because she was transcribing subscripts, but because she erroneously felt chloride ions were negative three (Cl^{-3}). rather than negative one (Cl^{-1}). Her diagram of the system on the reactants side was correct, her product side was correct with regards to the solid aluminum phosphate, however she shows the sodium chloride together. The solid aluminum phosphate was drawn at the bottom of the beaker, and her ability to keep the polyatomic ionic phosphate together had improved from her assessment on bonding.

Apparent Medium Achieving Student "Rebecca"

When reviewing the VNOS-B, Rebecca moved from inadequate understanding of theory versus law, adequate understanding of creativity and imagination and approaching informed for items the tentative nature of science, observation versus inference, myth of the scientific method and sociocultural aspects when completing her pre interventional VNOS-B questionnaire. Post intervention, she had grown to approaching informed for theory versus law, informed for the tentative nature of science, observation versus inference and myth of the scientific method. Her response to creativity and imagination had mixed results. Unfortunately, her response to sociocultural aspect of science dropped to adequate. Her delayed VNOS-B questionnaire appeared to be completed a bit more hurriedly and her coded responses reflected this shift, with her view of tentative nature falling to approaching informed.

Her post VNOS-B response

> "I believe that theories can change. *I believe that they can change because new data and evidence are found every day that could contribute the change of theories*. We bother to teach and learn ahem because it is information we still need to know. It can also help us with other theories too. *New data and evidence can expand our knowledge on the theory we're learning*. Making the theory change or not change based off our new knowledge. Still, teaching and learning these theories give us information we need. This can help us figure out other theories and science thin[king] in general"

A more succinct delayed VNOS-B response

> "I believe that the theory can change. *I believe this because new data and evidence are found out every time you do an experiment causing a theory to change.* We bother to teach and learn scientific theories because it *advances are [our] knowledge to be better scientists"*

When reviewing the BRI, Rebecca was able to respond correctly to items 1,2,4,7,8, 11,16,17, 19-21. Her results were slightly above the class average, and both 1-tier (11) and 2-tier (6) were above the historical data (Luxford, 2013).

The classroom assessment on bonding was above the class average. Her diagramming was similar to that of Samantha, however, rather than separate the carbonate in the copper II carbonate, she left the complex ionic compound together. Her ability to respond to the remainder of questions was also superior. Finally, when considering the RSCRDI, Rebecca performed a bit above her peers. She was able to respond correctly to both parts of expected items 1, 2, 15 and the bottom of 14; she was also able to respond correctly to both parts of potential item pairs 3, 10 and 13. She did not respond to unexpected item pairs correctly. The classroom assessment on reactions Her chemical equation was correctly written, with a unique error in her product. Rebecca placed the coefficient 3 between her Na and her Cl. This was an unusual mistake for this student to make, and the equation was correctly balanced, with the coefficient distributed throughout the entire compound. She was also able to provide the correct word equation.

Apparent High Achieving Student "James"

When reviewing the VNOS-B, James moved from a pre-interventional coded response with one informed, one inadequate and four adequate responses to all informed responses by the delayed VNOS-B. More specifically, James was coded as approaching adequate for creativity and imagination, adequate for items observation versus inference, theory versus law, myth of the scientific method and informed for the tentative nature of science. His post VNOS-B responses grew in each case, with the exception of the myth of the scientific method. His response for creativity and imagination grew to adequate and all remaining responses were informed. His delayed responses included clarifications for theory versus law, creativity and imagination and myth of the scientific method, which were written in a manner which the first author understood as informed, yet may have coded as approaching informed. However, James had been selected for a semi-structured interview and it was clear that his written responses had been interpreted correctly as informed. His interview resulted in an overall informed understanding of NOS.

For instance, in his delayed VNOS-B James did not clearly state that a law could change despite an overall informed description of inferences in theories and his ability to provide examples from outside of the current content (Atomic Theory and Laws of Motion) describing laws and theories in the written response.

Following up on question number three (*Is there a difference between a scientific theory and a scientific law? Give an example to illustrate your answer.*) The intent was to determine if the student was aware that laws and theories could change:

> Interviewer: "*When discussing theories and laws you mentioned that one is inferred (theory) and the other (law) observed. Would you say that one is more important than the other? May one or both change*?"
> James "*I don't think one is more important, they describe different things. They both have similar worth and both can change over time. Like, a law is observed and [they] can observe more which can change that law and for a theory it can change like the atomic theory which has been changed over time."*

For instance, in his delayed VNOS-B James stated the following in response to (item four):

> "Science and art are similar because *creativity must be used in the scientific process and the artistic process*. When coming up with a hypothesis, scientists must be creative. When artists thinking of a new piece, they also must be creative. They are different because *science requires precision* and art doesn't necessarily require that. When actually performing experiments *scientists must be precise and accurate.*"

However, the interview indicated an informed understanding of creativity and imagination:

> Interviewer: "*When you described how creativity and imagination applied to art and science you stated there was a need for precision and accuracy. Will you explain this response? In what ways are they being precise and accurate? When?"*
> James: "*In science a lot of the precise and accurate when doing calculation to get your math that you need and you need to be precise and accurate to get the correct data for different types of experiments and it is especially important if you are trying to make new discoveries; that would go with my previous one [statement]."*

When reviewing the BRI, James was able to respond correctly to 16 of the items which included items #1,2,6-8, 11 and 14 – 23. James's score was above the class average as one of the higher scoring students and the average 8.71 ± 3.20 tier -1 from Luxford (2013). Furthermore, his tier-2 score was 9; significantly above the mean of 4.27 ± 2.21 published by Luxford. The classroom assessment on bonding was without error. James was able to correctly identify and separate the ionic compounds for both the simple binary ionic compound and the complex ionic compound. He was also able to recognize and leave the covalent molecule together. The proportions for each electrolyte of the compounds were also correct, as were all charges and nomenclature.

As previously described, students were exposed to the content in the absence of contextualized NOS during the introductory unit chapter on reactions. Here, students were assessed using the RSCRDI and the classroom assessment. The results focus on expected (item pairs 1,2,4 and 15 and the bottom of 14), possible (3,10 and 13) and unexpected (5, 6 and 7) items from RSCRDI as well as selected items from the classroom assessment for which historical precedent was established.

Discussion

In the action research, students were introduced to NOS in the absence of content (decontextualized) later in the academic year. Their introduction included both student and instructor centered discussion of NOS aspects via the use of a modified Appendix H, with grade level exemplars and a handout with NOS aspects onto which students recorded their own descriptions of each aspect. The students also received instruction via activities such as a modified mystery tube activity.

Following the introduction to NOS, aspects were embedded within two units on bonding in an explicit-reflective manner. While bonding is an inaccessible concept, reflection questions were intended to assist with NOS comprehension in the context of bonding. These units took place over approximately seven weeks, after which students completed post VNOS-B questionnaires, a post BRI and classroom assessment. Students spent the next three weeks learning the introductory section on reactions. While the students were in the same cluster groups and the usual NGSS and three levels of representation were included in the absence of contextualized NOS. The students completed a delayed VNOS-B, post-RSCRDI and classroom assessment at the end of this unit on reactions.

The research question "How do students of differing ability levels conceptualize NOS and abstract chemistry concepts within explicit and reflective instruction?" allowed both increased research on explicit-reflective embedding of NOS within high school chemistry and a consideration of appropriate embedding of NOS within more abstract science concepts, such as chemistry. Lederman (2007) cautioned educators to consider the level of abstractness with contextualized NOS. The illustrative case study reflects heterogeneous college preparatory chemistry classroom students who may have been misplaced, at the lower academic ability level, average ability levels and those in slightly higher ability levels. The students who were medium ability level and above grew in the more sophisticated aspects of science comprehension such as observation versus inference, laws versus theories and tentative nature of science. However, the students in the lower achieving level or those who may have waved into the course or be misplaced struggled to gain informed or approaching informed NOS comprehension. These findings (without leveling) are similar to previous action research conducted in the primary author's classroom with more accessible content (Johnston & Akerson, 2022).

Additional insights gained from the action research indicated that students had reduced historical misconceptions during the chapters on bonding and reactions, as well as NOS. Students generally demonstrated an improvement to historical and published results for their post BRI as well as previous classes with the classroom assessment on bonding. These improvements in the content comprehension did appear to reflect apparent ability levels, with high and medium level demonstrating more growth from historical misconceptions. In general students demonstrated growth over on the post BRI assessment from the pre-BRI as well as what is in the literature (Luxford, 2013), students appeared to be less impacted by levels of representation than concepts which were relevant to their current curriculum. Field notes indicated that the tier-1 general results reflected growth (10.24 ±3.14) and an improvement over historical data (8.71 ±3.20) from the author of the BRI (Luxford). Field notes suggested the classroom assessment for bonding had improved on historical results when diagramming systems of simply binary ionic and covalent molecules in solution. Field notes reflected a 100 % improvement in the ability to separate binary ionic compounds in solution and a reduction in the separation of covalent molecules from 43% to 17% of students.

The reduction in misconceptions within bonding appears to impact student learning of reaction chemistry. In general, students grew in their ability to respond to expected, potential and even unexpected items of the RSCRDI. The different methods of implementation during the current action research study, where every effort was made to prevent prior exposure to items, and the initial use of the RSCRDI (Chandrasegaran 2007a) in which students completed each of the items during laboratories should be considered. It appears that students performed similar to historical data when considering the potential item #13, which included novel syntax such as spectator ions and ionic equations and applied double displacement reactions to the formation of a solid precipitate. They slightly underperformed when considering expected items #1 and 2, constituent atoms and the synthesis reaction of magnesium in diatomic oxygen. Students appeared to outperform when applying understanding to single displacement reactions forming diatomic hydrogen, in expected item #4. They also outperformed when responding to the possible item #3, an acid base reaction with no symbolic equation provided, identifying the cation responsible for the observed color and the product of the reaction; they also outperformed a second possible item #10, where all correctly described an acid base item without an equation provided in terms of the product and the formation of constituent atoms from an insoluble reactant.

The students improved on their ability to respond to items on their classroom assessment from previous years. The classroom assessment demonstrated anticipated levels of representation (*e.g.*, Ahmar et al, 2020) who suggest the submicroscopic levels with the lowest understanding. However, it is notable that all students demonstrated an understanding of polyatomic ions at the submicroscopic level, an improvement over previous students in the same classroom, and the literature (*e.g.*, Naah & Sanger, 2012; Nyachwaya et al., 2011).

The case study reflects growth at all levels, although the low achieving student did poorly when responding to the rigorous items of the RSCRDI, yet was able to respond to most of the open ended item with improvement on previous students, despite having more errors than her current peers. The student did demonstrate improvement of her understanding of polyatomic ions in her diagram.

Discussion of Case Studies

The findings overall and those of the case studies reflect a trend based on student apparent ability levels. The recommendations for chemistry educators include the use of VNOS-B to level students, how to utilize the results of VNOS-B questionnaires as part of pedagogical strategies, and suggested improvements for future research. To address recommendations for future research and the use of the current action research within instructional strategies should include a close look at the findings for each case study from the perspective of each research question to arrive at an overall consideration.

When considering the low-ability level student, Samantha, it is important to note that she was one of the most rigorous in her note taking and efforts within the classroom. She missed the fewest classes during the academic year and she attended at least one extra help session. Her efforts were also evident with notes she wrote which were beyond expectation and included in her assessments. It was apparent that Samantha was attempting to move from a rote approach to understanding the concepts. Her growth in NOS comprehension was impacted by small errors in these rote efforts. She was open to learning, yet also not inclined to adjust her work once she felt she had completed tasks. For instance, when a student requested a definition of magnesium ribbon, this student did not return to her questions and check to see if she had responded to the question using a correct definition. This was notable only because most students did return. She was usually one of the first to complete the assessments, and rarely posed questions for clarity. When completing the VNOS-B questionnaire, she did revert back from approaching informed to approaching adequate for the creativity and imagination in part due to syntax utilized to convey what she may have recalled and memorized prior to the questions. That is, when she was exposed to conversation about experience impacting the ability to notice and pre-emptively adjust within scientific experimentation, her expression and example included the ability to "*properly observe experimentation*" using creativity and imagination to describe bubbles more effectively as a "…*reaction looks as it is boiling*". Missing the fact that the creativity and imagination was applying why it appeared to bubble. As she moved into bonding and her assessments on bonding, the rote recollection was most notable on the open-ended assessment where she had written "*Ionic separates Covalent sticks*" and proceeded to diagram both the copper II carbonate and the magnesium chloride separated into constituent atoms, including the carbonate. For Samantha, her understanding at the time meant even the covalently bound polyatomic ion separated in an ionic lattice. As we moved from the embedded NOS instruction to reaction chemistry, Samantha was again one of the two lowest scoring students in general. Again, she proactively participated in group work, laboratories, note taking and had stellar attendance. Samantha attended an extra help session during this unit on reactions. The student was able to work through many practice problems, equations and diagrams with very little assistance from the other students or instructor. What was remarkable about Samantha's post instructional RSCRDI and classroom assessment for reactions was her approach to the assessments, her informed mistakes, and her growth in understanding of bonds. In previous academic years, students who struggled with bonding carried their confusion for creating formula units or reaction products, identifying reaction types, predicting if a reaction would occur and diagramming systems correctly.

However, Samantha was able to demonstrate her knowledge of reaction types based on notes written throughout both the RSCRDI and the classroom assessment. She wrote notes to herself such as "*… do not transcribe subscripts…*" or writing patterns and reaction types with appropriate patterns on items from the RSCRDI. It appears she may have compared the wrong items in one place and showing that she was able to transfer understanding of reactions to an unexpected item she would not have seen previously. Her classroom assessment also included additional notes such as "*remember crisscross method*" and indicating the reaction (which she was able to predict with the correct rearrangement of reactants to form aluminum phosphate and sodium chloride, the correct attempt at indicating the solid reaction product, and balanced equation. Her errors were limited to forgetting the chloride ion is not Cl^{-3} but rather Cl^{-1}

Samantha demonstrated the ability to diagram the system of reactants and constituent atoms correctly, including the ability to leave the phosphate ion together. Her products were correct with the exception of leaving her sodium chloride together (despite alluding to their dissolution by having the formula units moving and floating compared to the solid aluminum phosphate at the bottom of the beaker). Furthermore, her word equation was written flawlessly. Although Samantha represented one of the lowest performing students on the post assessments, she also reflects considerable improvement on the observed results from previous academic years. She did not incorrectly place negatives together, remove the subscript of four from the phosphate ion, transcribe subscripts, or incorrectly identify the reaction type. This student outperformed students from the literature (Nyachwaya et al., 2011) in which at least 9% of students demonstrated poor understanding of polyatomic ions diagrammatically, for instance separating them in solution. She was also able to provide the reaction type and a perfect word equation. Taber (2002) found the ability to create word equations important in both understanding bonding and how reactions occur. Her ability to grow at the symbolic and submicroscopic levels may indicate that despite errors in the chapter on bonding, some alternative understandings were mitigated in the subsequent chapter and she had moved away from solely memorizing toward understanding the concepts.

The medium-ability level student, Rebecca, was able to arrive at informed views of more sophisticated aspects of NOS such as tentative nature of science and observation and inference, approaching informed with her understanding of theories and laws and also informed in her understanding of creativity and imagination with respect to scientific process. The largest improvement for Rebecca was moving away from an inadequate understanding of theories versus laws to one which approached informed. She moved from the consideration of a theory as "*an estimate of what could happen*" and a law as "*there's no chance of laws changing*" to suggesting a theory was something "*inferred not seen while a law is observed*" or "*making a statement or observation based off of data and evidence.*" The suggestion that both theories and laws are capable of changing was what Rebecca did not mention in her responses. She also moved from using examples from her current concepts (*e,g,,* inference of ionic compounds turning on the lightbulb of a conductivity apparatus) and back to discussions of gravity. Rebecca is another student who does her best to be engaged within the classroom. She is one who will assist groups, and who also self-advocates by posing questions, as well as responding to questions from either the instructor or her classmates. She is also is quite involved in her school and did miss class over five times during the action research. She also posed questions for clarity when taking assessments. She did not attend extra help however, she wrote notes to self on some of the assessments, however they were limited to patterns for reactions and other strategies used to predict products. Her responses on the final VNOS-B appeared to be much shorter, indicating that perhaps she was experiencing a bit of assessment overload. As an employed student, Rebecca did occasionally forget to review for assessments, and this was evident in the final set of assessments. Her post BRI and classroom assessment on bonding demonstrated growth beyond historical results. She was able to respond correctly to most of the expected items on the BRI and her bonding assessment scored about average. Her scores were in the upper middle of her peers, with growth from previous student results. The first set of diagrams on her bonding assessment reflected her ability to separate the simple binary ionic compound and leave the covalent molecule together. Her confusion was noticed when she left the copper bound to carbonate in solution. This was an unusual error for Rebecca who had been able to complete practice without issues. As we moved into the unit on reactions, Rebecca was able to apply her understanding of bonding. She was able to predict products on laboratory activities and as she moved into the post instructional assessments. Her post RSCRDI was scored using her written test, as the Scantron® appeared to either skip responses or not reflect what was on her written assessment. Regardless, she was able to correctly respond to both expected and potential items correctly. This result indicated that she had responded correctly to items which may have been missed in the historical result, and which required a transfer of concepts to novel questions and reaction types. Her classroom assessment also demonstrated a level of understanding which was improved from her previous assessment, and which reflected an improved understanding over previous students in the classroom. She was able to predict the reaction products (although she did place a coefficient between the sodium and chloride, an error unique to Rebecca) the reaction was balanced correctly and diagrams also correctly reflected both the reactant and product side. Unlike Samantha, Rebecca was able to correctly diagram the solid ionic aluminum phosphate as the insoluble solid at the bottom of a beaker, while the sodium chloride was found separated into constituent atoms. Furthermore, her word equation was also written correctly.

As the work completed by Rebecca is considered, it is notable that she was able to successfully grow in her understanding of NOS and concepts in bonding, reducing historical misconceptions in the content. She was then able to respond to items on the post-RSCRDI which were beyond those expected and also demonstrate improved results on a three-part open ended classroom assessment item. Rebecca exemplified that average students (medium ability level) may have benefited and excelled during the unit on reactions by having a better understanding of bonding concepts as they began the chapter.

James who reflected a higher ability level student was an academically mature student and happy to share his work within his cluster group or with the whole class during reflections or instructional time. James was also adept at note taking, posing applicable questions, conducting laboratory activities and applying his understanding to novel concepts. James did not limit discussions within his cluster group, and was willing to alter his independent reflections to align with group consensus or to all his peers to arrive at a consensus without his input. They worked efficiently and appeared to enjoy the process. James grew in areas of understanding which allowed him to move toward informed understanding of each NOS aspect.

James was able to demonstrate understanding of bonding during both units, correctly responding to most reflection questions independently and leading his cluster group with discussions during the group component. His laboratory activities and practice were also stellar. James demonstrated nearly perfect understanding of bonding with both the BRI and the classroom assessment. He was able to move beyond the expected and respond to multiple unexpected items correctly. The classroom assessment on bonding was completed quickly and additional insights such as nomenclature and conductivity were added to diagrams. The aqueous systems included correct constituent atoms, as well as proportions. Similarly, when we moved into the unit on reactions, James was able to effectively respond to his laboratory activities and subsequent classroom assessment and post RSCRDI.

Limitations

The action research study was an important step toward better understanding how and when to include NOS within more rigorous science class concepts such as college preparatory chemistry. However, the nature of action research is limited in its inclusion of low numbers of students who are generally a convenience sampling of the educational researcher. In addition to the low numbers of students the action research also took place in the primary author's classroom introducing a potential for positionality. Additional limitations included the timing of the action research with multiple snow days and limited time to make up missed lessons due to high stakes district assessments and marking period deadlines.

Conclusion

Action research studies are performed within a teacher's classroom, and generally include a limited number of participants in a single environment. However, when conducting research with the intention of solving pre-existing concerns within the classroom, the experienced teacher may notice the impact of pedagogical adjustments quite readily. The student syntax during classroom discourse, the quality of practice, the overall confidence of the students and educator are amongst the non-quantifiable findings of the experienced educator. The primary author conducted the action research study and has over fifteen years of experience educating this level of chemistry student. The role of classroom teacher was also notable when inferring the written responses of students on the VNOS-B questionnaire. That is, intuited intentions of unclear responses were accurate following semi-structured interviews. Therefore, when considering inter-coder reliability, these insights may be useful when not anonymous.

In the action research study, students had not encountered formal instruction regarding NOS until the latter part of the second marking period. Students should be exposed to NOS in both decontextualized and contextualized contexts early in the academic year. In fact, NOS should be introduced as early as possible in a student's science instruction (Avsar-Ermut & Akerson, 2021). Furthermore, Lederman (2007) cautions educators about the incorporation of contextualized NOS within abstract content. While all students demonstrated growth in NOS views during the inaccessible units on bonding, lower achieving students did not appear to maintain informed views of NOS.

In addition to a leveled impact of growth in NOS comprehension, a correlation between level and growth in content was indicated. Here, students in the lower level appeared to rely on rote rather than understanding content, while medium and high level students did appear to mitigate previous misconceptions more readily. It is possible that students would benefit from earlier iterations of NOS embedded within more attainable chemistry content to enhance the growth and comprehension of both NOS and chemistry content for those in lower academic ability levels.

When considering growth in the subsequent unit, an introduction to reactions, a similar level was noticed. Here, each student appears to demonstrate improvement over historical classroom misconceptions. While the lower achieving students may continue to rely on rote learning, it was apparent that understanding of bonding was improved during the unit on reactions. For instance, the students all demonstrate the understanding of polyatomic ions, and the ability to correctly diagram them in solution. With earlier iterations of NOS, these students may improve on additional misconceptions.

Recommendations for Future Research

Future iterations of the action research may be repeated with a larger student population who are from multiple locations and a more diverse demographic. In addition, future iterations may also consider a few changes in the implementation of the action. To best understand how NOS embedded within the less accessible chemistry concepts enhances student understanding, earlier introduction to NOS within the chemistry classroom is suggested. That is, the research should be repeated with students who are versed in NOS aspects in a decontextualized manner in the first weeks of the academic year, followed by the inclusion of explicit-reflective NOS embedded within more accessible chemistry concepts. The action research presented in this publication limited the time during which students were exposed to NOS within the classroom. In future iterations, a return to organic instructional moments to emphasize NOS (during laboratories or as students make anticipated errors) should be considered. Once students have demonstrated growth in their NOS comprehension, the potential correlation between NOS embedded within less accessible concepts may be enhanced, notably lower achieving students may most benefit from earlier iterations of NOS. The pre-interventional VNOS-B may be completed at the beginning of the academic year, at mid-year a post-interventional VNOS-B may be administered and finally, an end of course secondary post-interventional VNOS-B may be administered. These questionnaires may be administered separately from the BRI, RSCRDI, and classroom assessments to reduce potential impacts of over-assessing.

Acknowledgements

Appreciation to Dr. Bretz for the use of the BRI and Dr. Treagust for the use of the RSCRDI. In addition, appreciation for the assistance offered by Mr. Michael Lonie and Dr. Andrea Padelsky as gatekeepers during the action research.

References

Ağlarcı, O., Sarıçayır, H., & Şahin, M. (2016). Nature of science instruction to Turkish prospective chemistry teachers: The effect of explicit-reflective approach. *Cogent Education, 3*(1), 1213350.

https://doi.org/10.1080/2331186x.2016.1213350

Akerson, V. L., Abd-El-Khalick, F. S., & 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.

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

Akerson, V. L., & Hanuscin, D. L. (2007). Teaching nature of science through inquiry: Results of a 3-year professional development program. Journal of Research in Science Teaching, 44(5), 653–680. https://doi.org/10.1002/tea.20159

Akerson, V. L., Nargund-Joshi, V., Weiland, I. S., Pongsanon, K., & Avsar, B. (2014). What third grade students of differing ability levels learn about nature of science after a year of instruction. *International Journal of Science Education, 36,* 244-276.

Ahmar,D.S., Azzajjad, M.F., & Muh. Syahrir (2020). Students' representation ability in chemistry. *Journal of Applied Science, Engineering, Technology, and Education*, *2*(2), 181–187. https://doi.org/10.35877/454ri.asci22124

Ariyarante, T. (2023). *Comparing scientists' views of the nature of science (NOS) with their demographic and fields of expertise*. [Doctoral Dissertation, Indiana University]

Avsar Erumit, B., Fouad, K.E. & Akerson, V.L. (2019). How do learner-directed scientific investigations influence students' questioning and their nature of science conceptions? International Journal of Education in Mathematics, Science and Technology (IJEMST), 7(1), 20-31. DOI:10.18404/ijemst.509246

Ayala-Villamil, L.-A., & García-Martínez, Á. (2020). VNOS: A historical review of an instrument on the nature of science. *Interdisciplinary Journal of Environmental and Science Education*, *17*(2), e2238. https://doi.org/10.21601/ijese/9340

Boo, H. K., & Watson, J. R. (2001). Progression in high school students? (aged 16-18) conceptualizations about chemical reactions in solution. *Science Education*, *85*(5), 568–585. https://doi.org/10.1002/sce.1024

Bowe, K. A., Bauer, C. F., Wang, Y., & Lewis, S. E. (2022). When All You Have Is a Covalent Model of Bonding, Every Substance Is a Molecule: A Longitudinal Study of Student Enactment of Covalent and Ionic Bonding Models. *Journal of Chemical Education*, *99*(8), 2808–2820. https://doi.org/10.1021/acs.jchemed.2c00188

Bugingo, J. B., Yadav, L. L., Mugisha, I. S., & Mashood, K. K. (2022). Improving teachers' and students' views on nature of science through active instructional approaches: a review of the literature. *Science & Education*. https://doi.org/10.1007/s11191-022-00382-8

Chandrasegaran, A. L. (2004a). *Representational systems and chemical reactions diagnostic instrument, RSCRDI.* [Unpublished Diagnostic Inventory], Arulsingam.; Curtin University of Technology. Science and Mathematics Education Centre.

Chandrasegaran, A. L. (2004b). Diagnostic instrument of secondary students' use of three levels of representation to explain simple chemical reactions. Doctoral Dissertation, Arulsingam.; Curtin University of Technology. Science and Mathematics Education Centre.

Chandrasegaran, A. L., Treagust, D. F., & Mocerino, M. (2007). The development of a two-tier multiple-choice diagnostic instrument for evaluating secondary school students' ability to describe and explain chemical reactions using multiple levels of representation. *Chem. Educ. Res. Pract.*, *8*(3), 293–307. https://doi.org/10.1039/b7rp90006f

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science & Education*, *15*(5), 463–494. https://doi.org/10.1007/s11191-005-4846-7

Clough, M. P., Herman, B. C., & Smith, J. A. (2010). *Seamlessly teaching science content and the nature of science: Impact of historical short stories on post-secondary biology students*. In Association for Science Teacher Education (ASTE) National Conference, Sacramento, CA.

Clough, M. P., & Olson, J. K. (2007). Teaching and assessing the nature of science: An introduction. *Science & Education*, *17*(2-3), 143–145. https://doi.org/10.1007/s11191-007-9083-9

Deng, F., Chen, D.-T., Tsai, C.-C., & Chai, C. S. (2011). Students' views of the nature of science: A critical review of research. *Science Education*, *95*(6), 961–999. https://doi.org/10.1002/sce.20460

Demirdöğen, B., & Uzuntiryaki-Kondakçı, E. (2016). Closing the gap between beliefs and practice: Change of pre-service chemistry teachers' orientations during a PCK-based NOS course. *Chemistry Education Research and Practice*, 17(4), 818–841. https://doi.org/10.1039/c6rp00062b

Dogan, N., & Abd-El-Khalick, F. (2008). Turkish grade 10 students' and science teachers' conceptions of nature of science: A national study. *Journal of Research in Science Teaching*, *45*(10), 1083–1112. https://doi.org/10.1002/tea.20243

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young People's Images of Science*. McGraw-Hill Education (UK).

Gillespie, R. J., & Nyholm, R. S. (1957). Inorganic stereochemistry. *Quarterly Reviews, Chemical Society*, *11*(4), 339. https://doi.org/10.1039/qr9571100339

Johnston, M. F. & Akerson, V. L. (2022). Nature of science in an NGSS chemistry classroom. In V. L. Akerson & I. S. Carter (Eds.), Teaching Nature of Science Across Contexts and Grade Levels: Explorations through Action Research and Self Study (pp. 25-68). ISTES Organization.

Johnston, M. F. & Lane, K. D. (2022). Embedding nature of science explicitly within an NGSS chemistry classroom – A self-study. In V. L. Akerson & I. S. Carter (Eds.), Teaching Nature of Science Across Contexts and Grade Levels: Explorations through Action Research and Self Study (pp. 243-266). ISTES Organization

Johnston, M.F. (March 26-30, 2023). NOS in an NGSS chemistry classroom. Presentation for American Chemical Society: Crossroads of Chemistry. Indianapolis, Indiana.

Johnston, M. F. (2024, June). *The impact of nature of science on student epistemological misconceptions in nature of science, bonding and reaction chemistry*. Handle.net; [Bloomington, Ind.]: Indiana University. https://hdl.handle.net/2022/30125

Johnstone, A., (1982) "Macro- and microchemistry" *School Science Review* vol.64 pp.377-379

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

Kind, V. (2004). *Beyond Appearances: Students' misconceptions about basic chemical ideas 2 nd Edition*. https://edu.rsc.org/download?ac=15564

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching, 29*(4), 331–359. https://doi.org/10.1002/tea.3660290404

Lederman, N.G. (2007). Nature of science: Past, present, and future. In S.K. Abell and N. G. Lederman (Eds) *Handbook of Research on Science Education.* pp. 831-880. Mahwah, NJ: Erlbaum.

Lederman, N. G., Abd-El-Khalick, Bell, & Schwartz. (2002). Views of nature of science questionnaire (VNOS): Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*, 497-521.

Lederman, N. G., Bartos, S. A., & Lederman, J. S. (2014). The development, use, and interpretation of nature of science assessments. *Springer EBooks*, 971–997. https://doi.org/10.1007/978-94-007-7654-8_29

Luxford, C. J., & Bretz, S. L. (2014). Development of the bonding representations inventory to identify student misconceptions about covalent and ionic bonding representations. *Journal of Chemical Education*, *91*(3), 312–320. https://doi.org/10.1021/ed400700q

Luxford, C. J. (2013). *Use of Multiple Representations to Explore Students' Understandings of Covalent and Ionic Bonding as Measured by the Bonding Representations Inventory* [Doctoral dissertation, Miami University]. OhioLINK Electronic Theses and Dissertations Center. http://rave.ohiolink.edu/etdc/view?acc_num=miami1366031143

Majeed, S. (2023). An exploration of students' common misconceptions in the subject of chemistry at secondary level. *Annals of Human and Social Sciences*, *4*(II). https://doi.org/10.35484/ahss.2023(4-ii)25

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

McComas, W. F., & Clough, M. P. (2020). Nature of Science in science Instruction: Meaning, advocacy, rationales, and recommendations. *Science: Philosophy, History and Education*, 3–22. https://doi.org/10.1007/978-3-030-57239-6_1

McComas, W., & Nouri, N. (2016). The Nature of Science and the Next Generation Science Standards: Analysis and critique. *Journal of Science Teacher Education, 27(5)*

Michel, H., & Neumann, I. (2016). Nature of science and science content learning. *Science & Education*, *25*(9-10), 951–975. https://doi.org/10.1007/s11191-016-9860-4

Naah, B. M., & Sanger, M. J. (2012). Student misconceptions in writing balanced equations for dissolving ionic compounds in water. *Chem. Educ. Res. Pract.*, *13*(3), 186–194. https://doi.org/10.1039/c2rp00015f

Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education*, *69*(3), 191. https://doi.org/10.1021/ed069p191

NGSS Lead States. (2013a). Next Generation Science Standards: For States, By States. Appendix H – Understanding the Scientific Enterprise: The Nature of Science in the NGSS. http://www.nextgenscience.org/next-generation-science-standards [select Appendix H].

NGSS Lead States. (2013b). Next Generation Science Standards: For States, By States (Lead State New Jersey). Retrieved from https://www.nextgenscience.org/lead-state-new-jersey

Nouri, N., Saberi, M., McComas, W. F., & Mohammadi, M. (2021). Proposed teacher competencies to support effective nature of science instruction: A meta-synthesis of the literature. *Journal of Science Teacher*

Education, *32*(6), 601–624. https://doi.org/10.1080/1046560x.2020.1871206

NSTA. (2020, January). *Nature of Science | NSTA*. Www.nsta.org. https://www.nsta.org/nstas-official-positions/nature-science

Nyachwaya, J. M., Mohamed, A.-R., Roehrig, G. H., Wood, N. B., Kern, A. L., & Schneider, J. L. (2011). The development of an open-ended drawing tool: an alternative diagnostic tool for assessing students' understanding of the particulate nature of matter. *Chem. Educ. Res. Pract.*, *12*(2), 121–132. https://doi.org/10.1039/c1rp90017j

O'Connor, C., & Joffe, H. (2020). Intercoder reliability in qualitative research: Debates and practical guidelines. *International Journal of Qualitative Methods*, *19*. https://doi.org/10.1177/1609406919899220

Peters, E. (2012). Developing content knowledge in students through explicit teaching of the nature of science: Influences of goal setting and self-monitoring. *Science & Education*, *21*(6), 881–898. https://doi.org/10.1007/s11191-009-9219-1

PHET Interactive Simulations. (2021). *Molecule Shapes*. PhET. https://phet.colorado.edu/en/simulations/molecule-shapes

Ralph, V. R., States, N. E., Corrales, A., Nguyen, Y., & Atkinson, M. B. (2022). Relevance and equity: Should stoichiometry be the foundation of introductory chemistry courses? *Chemistry Education Research and Practice*, *23*(3), 662–685. https://doi.org/10.1039/d1rp00333j

Taber, K. S. (2018). Alternative conceptions and the learning of chemistry. *Israel Journal of Chemistry*, *59*(6-7), 450–469. https://doi.org/10.1002/ijch.201800046

Taber, K. S. (2002.). *Chemical misconceptions I: Chemical reactions*. RSC Education. Retrieved October 4, 2023, from https://edu.rsc.org/resources/chemical-misconceptions-i-chemical-reactions/1141.article?adredir=1

Taber, K. S. (2019). Conceptual confusion in the chemistry curriculum: Exemplifying the problematic nature of representing chemical concepts as target knowledge. *Foundations of Chemistry*, *22*(2), 309–334. https://doi.org/10.1007/s10698-019-09346-3

Taber, K.S. (2013). Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemistry Education Research and Practice*, *14*(2), 156–168. https://doi.org/10.1039/C3RP00012E

Torres, J., & Vasconcelos, C. (2019). Prospective science teachers' views of nature of science: Data from an intervention programme. *Eurasia Journal of Mathematics, Science and Technology Education*, *16*(1). https://doi.org/10.29333/ejmste/110783

Tsaparlis, G., Pappa, E. T., & Byers, B. (2018). Teaching and learning chemical bonding: Research-based evidence for misconceptions and conceptual difficulties experienced by students in upper secondary schools and the effect of an enriched text. *Chemistry Education Research and Practice*, *19*(4), 1253–1269. https://doi.org/10.1039/c8rp00035b

Wahbeh, N. & Abd-El-Khalick, F. (2014). Revisiting the translation of nature of science understandings into instructional practice: Teachers' nature of science pedagogical content knowledge, *International Journal of Science Education,* 3693), 425-466, DOI: 10.1080/09500693.2013.786852

Yitbarek, S. (2011). Chemical reaction: Diagnosis and towards remedy of misconceptions. *African Journal of Chemical Education*, *1*(1), 10–28.

Author Information

Mary F. Johnston	Valarie L. Akerson
https://orcid.org/0000-0002-0682-011X	https://orcid.org/0000-0002-0945-6149
Indiana University	Indiana University
Bloomington, Indiana	Bloomington, Indiana
USA	USA
Contact e-mail: *MFJohnst@IU.Edu*	