Investigating General Chemistry Students' Ideas of the Role of Scientific Instruments

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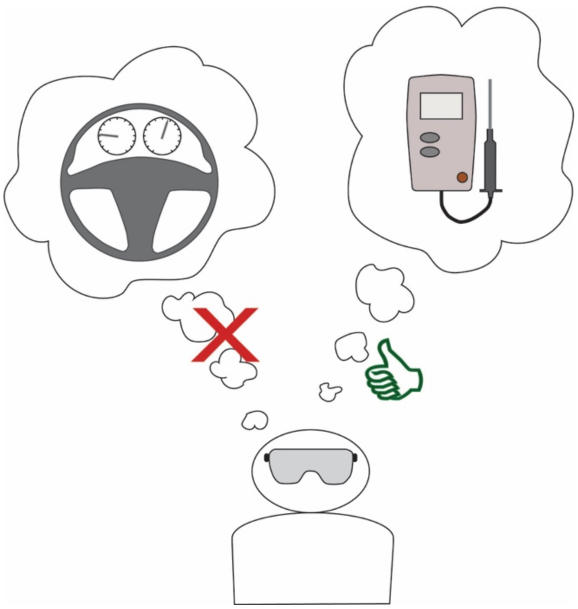
Abstract

Scientific instruments have long been a vital part of science, paving pathways to remarkable scientific advancements. Such advancements have changed the world both socially and culturally, especially in the past few decades. Students can be introduced to this idea through the concepts of nature of science (NOS): scientific observations are often filtered through apparatus, inferences can be made through observations, and science is a socially and culturally embedded practice. The curriculum often fails to emphasize the role of instruments in scientific practices, even in teaching laboratories. This study uses semi-structured interviews to investigate the cognitive (thoughts) and affective (feelings) domains of first-year university students as they relate to scientific instrumentation, including students' ideas of instruments. First, the study probed how general chemistry students conceptualize scientific instruments in relation to the three NOS notions. Secondly, students' practices related experimental data evaluation was investigated as data collection is a large part of psychomotor learning in laboratory. Third, students' affective states towards learning about instruments were queried. The interview results suggested that a majority of participants acknowledge some ideas of NOS, while a few students displayed an advanced understanding when discussing scientific instruments and also tended to have higher interest and motivation towards learning about instruments.

Keywords

First-Year Undergraduate/General, Laboratory Instruction, Chemical Education Research, Instrumental Methods, Nature of Science

Graphical Abstract



Introduction

This statement from one of the opening paragraphs to Holmes' and Levere's book, *Instruments and Experimentation in the History of Chemistry*, [1] provides an insight into chemistry and its history.

"This science [chemistry] has been, from its very beginnings, defined by instruments and apparatus comprising a repertoire of laboratory operations that its practitioners have employed to examine experimentally natural materials or the fabrications of human culture. […] the history of chemistry has been overwhelmingly a history of chemical theory, with practice little considered and with the apparatus that rendered that practice possible almost entirely ignored" (pg. vii-viii).

If scholarship in the history of chemistry has tended to focus on chemical theories, it may be unsurprising that chemistry education tends to share this emphasis. The missed opportunity, however, is that students who learn theories without thinking of observations they explain only see a part of the power of chemistry and chemical thinking. A scientific instrument has been defined as "any specific contrivance or aid which may be used to carry out any particular physicochemical operation".[2] As reflected by the quote, instruments encompass a wide range of tools. The development and the existence of various scientific instruments dating back to 1500s,[1] and especially in the past 100 years, have allowed science to advance rapidly.[3] Still, students in science classes typically learn relatively little about science history, and partly as a result are often unaware of the role of instruments in advancing science and scientific thinking.

Instruments in Education and Nature of Science

Advocating experimental science in education began in the early nineteenth century.[1,4,5] Since then, laboratory activities have been not only a place where concepts were illustrated, but also where the nature of science could be understood by students.[4,6] Nature of Science (NOS), defined as epistemology of science,[7,8] has been a long-supported concept in science education.[9-12] A major motivation behind the support of incorporating NOS in science courses is to mold scientifically literate students.[9,11-14] Being scientifically literate involves understanding how scientific knowledge is generated,[13,14] which requires the understanding of several NOS ideas.

While different definitions and scopes of NOS exist in literature, there are some commonly agreed upon notions of NOS.[7,8,15] Among them are the empirical characteristic of science, the distinction between observations and inferences, and the idea that science is socially and culturally embedded.[13] The empirical nature of science refers to the fact that scientific observations are "filtered through the human perceptual apparatus",[8,16] where direct observations of natural phenomena are often not obtainable. Related to the idea of observation is the difference between observations and inferences: observations are “descriptive statements about natural phenomena” (e.g., seeing an object fall to the ground), whereas inferences are “statements about phenomena that are not directly accessible to the senses” (e.g., the notion of gravity).[8] Lastly, science as socially and culturally embedded practice denotes how science is not only affected by society and culture, but it is also part of our everyday lives.

While NOS encompasses several other concepts regarding scientific knowledge,[7,8,15-17] the empirical way of knowing, observations and inferences, and sociocultural science are three ideas especially relevant to scientific instruments that are discussed in this study. Ultimately, observations that can be made with human senses are limited, and much of scientific knowledge is obtained with observations made with instruments, which allow the creation of inferential theories. A prominent current Earth and societal concern illustrates the importance of this connection. Climate change and global warming is one area where the role of scientific empirical ways of knowing, including uncertainty associated with inferences, has been studied.[18] The manner in which scientists understand the role of instruments and their limitations differs from much of the general public, and policy debates around topics like climate change highlight the importance of the sociocultural embeddedness of science. Connections such as these benefit from building the awareness of science students about how their empirical observations are understood.

Ultimately, students who complete a chemistry degree experience the role of instrumentation at several points in the curriculum. Such students are exposed to nuanced views of the distinction between observations of nature and the concept that instruments make measurements that are often processed electronically before being used to infer something about the system under study. General chemistry, however, is taken primarily by students who will not major in chemistry, and considering a more simplified view of the role of instrumentation can introduce this larger variety of students to the empirical ways of knowing within chemistry. This "service" role for introductory chemistry provides the motivation for the qualitative work presented here and the level at which instruments are discussed in the course, and in the research conducted.

Instruments in Chemistry Laboratory

Although laboratory has been long regarded as an essential part of chemistry learning, the question of whether laboratory courses are worth the cost, both in term of expense and labor, has been raised repeatedly.[19,20] The laboratory is said to be "*the place where students learn how to do chemistry*",[21] and this idea calls for the incorporation of the NOS.[7] However, Russell and Weaver's study of traditional, inquiry-based, and research-based laboratory curricula concluded that the traditional curriculum makes little impact on students' understanding of the NOS ideas.[22]

Chemistry laboratories in higher education often incorporate various types of instruments to enable measurements and observations that human senses cannot directly detect. These instruments are powerful tools used in modern chemistry, and students' experiences with them can have several benefits.[23] Some of the benefits of early exposure to instruments were provided by Steehler in his commentary to this *Journal*: "…including the motivating connection to real-life chemistry, the complementary nature of the type of laboratory experience, and the need to start learning these powerful [modern chemistry] methodologies".[23] Despite these benefits, many instruments are perceived by students as "black boxes",[23-25] meaning users are only concerned with instruments' functions rather than *how* they function.[26] This phenomenon may partially be an outcome of the curriculum's frequent emphasis on the manipulation of numerical data provided by instruments. Additionally, the idea that instruments enable humans to make scientific observations and inferences (empirical NOS & observation and inferences NOS), and that they have wide applications outside of educational laboratories (social and cultural NOS), are often not highlighted in chemistry courses. While experimental procedures and data are important, it is also essential to help students understand how scientific information is acquired[3] (i.e., empirical NOS).

Significant effort in chemistry education research is directed at exploring how to improve laboratory education.[19, 27-36] Among these reports, a limited number of studies focuses on instrument usage in chemistry laboratories.[37-41] Furthermore, studies that focus on both cognitive and affective aspects of laboratory learning centered around instrumentation are even more scarce.[42,43] Assessing cognitive and affective aspects of learning becomes especially important when considering the concept of meaningful learning. Meaningful learning, defined as construction of one's own knowledge, requires an engagement of affective ("feeling"), cognitive ("thinking"), and psychomotor ("doing") domains.[6,44-45] Laboratory courses are inherently oriented towards psychomotor learning domain,[46] making the "doing" part of the meaningful learning inevitable. Actions such as following experimental procedures and manipulating various instruments constitute a psychomotor portion of learning. However, students affective and cognitive domains in relation to instrumentation have not been investigated extensively. Thus, in order to ensure effective laboratory education involving instruments, how students think (cognitive) and feel (affective) should also be studied.

A limited number of studies provide some insight into students' cognitive and affective learning involving instruments. In a study where students' conceptual understanding as well as their attitude towards instruments were assessed, it was found that students generally held positive attitudes about using instruments because of their connection to "real world".[42] Based on their findings, the authors suggested that laboratory experiments should emphasize theory, purpose, and capabilities of instruments and techniques rather than repetitions of procedures.[42] Warner et al. investigated the impact instruments had on student learning in undergraduate laboratories.[43] They observed that the exposure to instruments through practical, hands-on activities affected how students perceived instrumentation.[43] For example, simply discussing instruments in lecture and laboratory without the hands-on exposure resulted in decline of knowledge about instrument operation and data.[43] Improvement in problem solving abilities through instrumentation was also observed when students had more chances to work with instruments in similar contexts.[43] Similarly, an investigation of analytical chemistry students' interaction with a CCD spectrophotometer revealed that students' perception of instruments can depend on experimental designs and goals.[47-49] Schmidt-McCormack's more recent study indicated that videos on pre-laboratory, experimental, and data analysis supported upper-division chemistry laboratory students in completing their experiments, including their use of instruments.[50] The authors noted that while the use of such videos can help students make connections among pre-laboratory lectures, experiments, and their autonomy, more cognitive support for students' laboratory learning would be necessary based on the survey results.[50]

Current Study

Nature of science concepts encompass the idea that many scientific understandings, and the ability to make inferences, stem from the availability of instruments. Combined with the aforementioned studies, while they are limited in scope, the importance of instrumentation in chemistry learning is clear. Introducing students to the idea of NOS that science is empirical, where instruments provide a way of making indirect observations of natural phenomena, may provide important ways to increase science literacy and instill deeper understanding of how science operates. In addition, science is not separable from broader society, and amplifying this view in chemistry education is deemed valuable as demonstrated by several reports.[34-36,51,52]

However, it is largely unknown the ways that students perceive the roles of instruments in science and society. In order for general chemistry courses to be able to incorporate the broader ideas of science based on observations in NOS, it is necessary to first assess the level of awareness students possess about instruments and their purposes. This study was conducted using a semi-structured interview approach to probe students' understanding of NOS in relation to instruments, and to assess their affective states toward scientific instruments. The first research question spans both key NOS ideas and was hypothesized to allow an exploratory investigation of students' current views of instruments. Interview questions were developed to reflect the NOS ideas more specifically. Understanding students' affective domain was an important part of this study for reasons such as its importance in the road to meaningful learning and the scarcity of studies connecting affective domain and instrumentation.

Research Questions:

1. In what ways do general chemistry students conceptualize the role of scientific instruments, and how does that process reflect key aspects of the nature of science?
2. How does an understanding of scientific instruments influence the interest of general chemistry students in experimental science?

Methods

The current study was carried out at a large public University in the Midwest region during Summer and Fall 2019 semesters. All procedures were approved by the Institutional Review Board (IRB) prior to the study.

Context

The interview participants were recruited from the first-semester General Chemistry course (GC-I). Per IRB agreement, participation in this study was strictly voluntary, and an announcement about the study was made in each section of GC-I by the researcher in the first or second week of the semester.

Interview development and data collection

To provide the opportunity to obtain more nuanced views students hold about instrumentation, semi-structures interviews were held with student volunteers from the general chemistry course. Questions for the interview protocol were developed under four ideas: (1) how students think instruments are used in science, (2) how instruments are used outside of science, (3) their thoughts on data evaluation, and (4) their interest and motivation towards learning about instruments. Initial scripted interview questions were written by the researchers and refined through a series of discussions (Table S1, SI). The first two ideas allowed us to explore students' understanding of instruments related to the NOS notions that science is empirical and socially and culturally embedded. The idea about data evaluation stemmed from the fact that part of psychomotor learning students experience in laboratory comes from collecting data, and that prior literature on laboratory learning has discussed the importance of fostering students' focus on quantitative data in traditional laboratory courses.[53] Thus, it was of interest in this study to explore how students engage in evaluating the data obtained from instruments. The third idea is also related to the empirical NOS and the differentiation between observations and inferences. Lastly, the fourth idea was added to investigate students' feelings towards instruments, as affective domain is an important component of meaningful learning. While the fourth idea was not explicitly related to the concepts of NOS, we hypothesized that students who recognized social and cultural NOS would also show positive attitude towards learning about instruments.

Potential interview participants were identified via a class-wide survey distributed at the beginning of the semester as part of a larger study. Out of 68 students who indicated initial interest, 14 students agreed to participate in interviews. All participants were enrolled in GC-I and the corresponding laboratory course during the semester in which the study was carried out. Each interview participant was provided with a consent form prior to the interview, and all interviews were carried out in a private room. The list of interview questions is included in Supporting Information (Table S1). Follow-up questions were mainly used to prompt students to provide more detail about their initial responses. The interviews were audio-recorded and lasted 36 minutes on average. All interview participants received a $10 gift card as compensation for their time. Interviews were transcribed, verbatim for further analysis.

Interview data analysis framework

An inductive coding process[54] was undertaken, where common themes were identified from the data.[55] After repeated review of transcripts, commonly arising themes were combined to create codes.[56-59] Initial draft of the codebook was continuously revised through discussions, coding of transcripts, and comparison of codes between two researchers who taught in the general chemistry laboratory program. The credibility of the codes and the findings from the data were reviewed in weekly meetings with a larger group of researchers. This process was repeated until >95% consensus[60-62] was reached between the two coders.

The first type of codes generated through the inductive coding process align with three domains of meaningful learning: cognitive (C), affective (A), and psychomotor (Pm). Thus, for example, when a participant in an interview made a statement related to a cognitive perspective of instruments in science, a code “C” was recorded. All student responses to prompts pertaining to conceptualization of scientific instruments were identified as cognitive based, and thus resulted in “C” codes. For such prompts no “A” or “Pm” codes were assigned from the student interview data. In addition to the codes aligning with these three domains of meaningful learning, participant interviews included statements that were captured with additional subcategories that were directly connected to instrument usage. For example, when a participant cited a specific example of instruments the code (IEX) was assigned. Similarly, examples of instrument usage (EX), and purpose of instruments (P) were used by some participants and captured with the appropriate code. Lastly, numerous sub-codes were devised along with the C, A, Pm, IEX, EX, and P codes to allow more nuanced assignments of codes for participant statements. These sub-codes were often necessitated when participants were describing their reasoning related to an answer of a question prompt or follow-up question. For example, when a student responded that instruments are useful, they were prompted to provide a reasoning for that response. These reasonings, such as usefulness for future careers or their ability to provide accurate measurements, were coded using the sub-codes. The full and final version of interview codebook can be found in Table S2 of Supporting Information.

Findings

The findings from this analysis are presented within three categories. We begin with participant views on instruments first, and views on data analysis second. Finally, the focus turns to how students view learning about instruments. Connections to the role of NOS, which touch on each of these categories, are made throughout the discussion of findings in order to emphasize that role throughout all aspects of the study.

Views on Instruments

The first part of this study explored students' perception of instruments including the cognitive domain aspect of meaningful learning, as well as several connections to NOS concepts. Examples of scientific instruments provided by students tended to be the ones they are familiar with through science labs or recent experiments. For instance, commonly mentioned instruments were a thermometer, beaker/flask, graduated cylinder, calorimeter, pipette, and hotplate. In addition, some students also talked about a burette, ruler, microscope, scale, and stopwatch or clock. Many of the items (e.g., beaker, pipette) are universally used not just in general chemistry laboratories, but in science laboratories as a whole. Instruments such as a calorimeter and microscope appeared to be mentioned by students who had recently completed experiments involving them, whether in chemistry or in other science courses. A computer, dissection tools, calculator, x-ray, oven, and various types of sensors and gauges were mentioned as examples of instruments, but less often.

Students were asked to describe the utility of the example instruments they provided, and several aspects were noted. One of the reasons all interviewees stated was the instruments' function of measuring a variable (e.g., volume, mass, temperature). Glassware such as beakers were justified by their ability to aid in experiments. A few students (n = 4) specifically mentioned that the function of instruments is allowing humans to observe or do what would otherwise be impossible. An example of this is represented by Student 2's response:

> Student 2: "[…] usually the things that we studied are things that aren't really obvious. So like the smaller things, you'd have to use something to get...like, same with the microscopes, like you'd have to use something to be able to see what we can't see with the naked eye."

When the participants were asked to explore further, to consider the general purpose of instruments rather than only their utility, similar responses were noted. A majority of students placed an emphasis on instruments' measurement abilities, with some students recognizing their overall capability in helping humans carry out scientific processes.

Student 10: "I think it just helps us to find the answers of different questions that we would otherwise use longer procedures to."

Student 11: "Um, I would say, to like, help them do, like, the most accurate research, like, get the most accurate results, as they can, and like, be able to conduct any experiment that they want, to so that they can either figure something out, like prove, prove something or like, disprove something."

The role of NOS that emerges from this component of the student interviews is the common perspective that they connect to the notion of empirically based scientific knowledge. Specifically, participants viewed instruments as a platform to observe what cannot be observed with human senses. Overall, only a small number of participants made this connection explicitly, while other students emphasized on how instruments function as measurement tools presents a more nascent perspective of the empirical basis of science. That even a small percentage of participants were able to explicitly connect the role of instruments to seeing otherwise unobservable phenomena suggests that for a given population of general chemistry students some may hold a relatively informed view of instruments in science and in the way science advances.

In order to reveal any additional student insights beyond their classroom experience of instruments, participants were prompted to think of an example where scientific instruments are used in life outside of laboratory (Q5, Table S1). Most interviewees gave examples such as measuring ingredients for baking or measuring dimensions with a ruler or a tape measure, primarily involving the idea of measurement in everyday life. Though simple, these examples provide preliminary evidence that students possess an ability to articulate the sociocultural-embedded aspects of science upon general prompting. It is worth noting that for most participants, the type of measurement described in their response was relatively direct, however, such that inference from the measurement to the data was straightforward.

More technology connected measurement tools that were noted by some students were speedometer in automobiles and global positioning system (GPS). While many students thought of the aforementioned examples relatively easily, two students struggled to find any example at first, stating that instruments are not used outside of science. These two students, perhaps representing a small proportion of general chemistry population, were either unaware of how instruments are embedded in our lives or have developed strongly compartmentalized knowledge about chemistry classwork relative to NOS and did not see how to extend that understanding into contexts that are not specifically in the context of course work.

Participant responses in the interviews quickly established the strong tendency to relate instruments to educational laboratory settings. This idea was unsurprising, and completely reasonable. Even within this large category, however, there are nuances about student understanding of instruments in the laboratory that merit further elaboration. For instance, the benefit of instruments in the laboratory setting was noted, such as when Student 4 said:

> Student 4: "As a student, like, taking chem lab and stuff, I think that they're all really like beneficial and I use them a lot"

Some students acknowledged that there are probably more applications and usages outside of science and school that they are not aware of, or that their usages have become a second nature. Students 3 and 14's responses illustrate these ideas:

> Student 3: "I think they're probably a lot more relevant than I think they are. Like, they're probably in my life more than I think about them being there, if that makes sense."

Student 14: “I... I use... I guess, like, I use them every day. And I don’t even realize it. And I think, like, that applies to a lot of things, even a simple thing like a clock. You use that all the time to measure, and... rulers all the time. Just kind of become a second nature. Like those little, like, everyday basic things that also apply to lab. Even thermometers. Yeah.”

Other students expressed a combination of the two ideas, where they thought there are more uses of instruments related to them, but the connection was still primarily through school:

Student 7: “I think, in like, a raw, like, I'm sure there are a lot that I use in my life that I’m just, like, not thinking of as scientific instruments. But mostly what I think of is like through school.”

Beyond recognizing basic uses of instruments in contexts outside of laboratory through cooking or other measurements, it was clear that the students struggled to deeply connect themselves to scientific instruments. Some students were aware there may be more uses, but they were unsure of what those uses might be outside of laboratory courses, showing the limited understanding of the sociocultural-embedded NOS. However, three students seemed to understand the close relationships we have with instruments as well as the interconnected nature of instruments. The response from Student 6 depicts this idea:

Student 6: “I mean they're, they're...they’re integral components of things that we use on daily basis […]. I mean, like, generally we just, we don't live in naturally intended lifestyle. Like, we are in a building, with tools that you need scientific instruments to use, […], to operate. So, yeah, it’s fundamental piece that affect every part of our lives.”

Karakas presented a study assessing science instructors’ ideas of NOS and found a majority of participating instructors recognized the inseparable nature of science and human lives, portraying the idea that science is socially and culturally embedded.[13] Certainly, some interviewees here possessed a similar level of connection between science and society. Overall, however, the interview data from this study suggest that a modest fraction of students appear to be aware of the sociocultural nature of science. This observation, with participants drawn from a largely traditional general chemistry course presents some concerns, given that literature emphasizes the need for science education to represent the sociocultural attribute of science.[7,9,12]

Beyond discussions about the aspects of instruments in both science and life, the depth of awareness students had about the connection of instruments in the two contexts was probed. The interviewees were asked to think of things still possible or impossible without instruments in the world (Q10 & 11, Table S1). Given this prompt, many students were concerned about the lack of quantitative data or accuracy of measurements, and Student 3's response shows this idea:

> Student 3: "I feel like we wouldn't be able to put numbers to things. So, like, whenever we apply it, so measuring out miles when you drive or something like that, like, I feel like that factor would just be taken out."

Another common idea participants suggested about the absence of instruments was the possibility of difficulties in scientific processes, such as making discoveries of gases or atomic composition. Student 2 said:

> Student 2: "Maybe like...atomic composition, so like, we can't really grab an atom and be able to understand what, what's going on. So, you're going to need all these different experiments to figure out like, oh, there's a nucleus, there's a negative charge positive charge, things like that. And we can't really do that on our own."

In this quote, Student 2 is synthesizing an understanding of the empirical nature of science by recognizing that some observations or inferences would be impossible to make without instruments. In total, three students recognized a wider impact that the absence of scientific instruments could bring, not just related to scientific experiments but also connected to the society. Take a look at Student 13's response:

> Student 13: "Wow, the implications of that question...Um... We wouldn't be nearly as far along. Specifically, the world of chemistry. [...] And without the discovery of the right instrument for the job, the process at which like that specific instrument was made for wouldn't ever had been finished. And outside of chemistry. I mean, if we look at our, look at cars, for example, like they are, really, they are a piece of science, and the way they work and how we're moving forward with electric cars. And if we didn't, with electric cars, if we didn't have computers and different

things, we wouldn't be able to model them and tune them and make them function properly. And so, I think, yeah, we'd be in a pretty sorry place."

Clearly, Student 13 and two other interviewees recognized that instruments were not confined to the world of science, and that their influences reach the aspects of life that we all experience on daily basis. Their view of instruments and science, represented by Student 13's response, is in line with both empirically based and sociocultural-embedded NOS.

Nonetheless, in spite of these examples, the idea that using measurement, focusing exclusively on the quantitative measurement and data output functionality of instruments, was routinely presented by the students. This observation further elaborates the tendency of students to identify the focal point of chemistry laboratory courses. This observation is likely tied to the fact that the students were enrolled in a chemistry course, and that they were aware the interview was related to their chemistry course experiences.

As interviews appeared to suggest that students seemed to understand the impact instruments had on scientific discoveries, it was useful to consider the students' perceptions of the way science moves forward. Thus, students were asked whether they thought instruments have contributed to scientific advancement (Q13, Table S1). All interview participants agreed that instruments indeed have made contributions, though their reasonings and the degree of acknowledgement varied. For example, Student 4 said:

Student 4: "I would definitely say so. Because of, like, what we were saying earlier about, like, being able to be sure of something, like, the mass or volume, even. If you were never, like, sure about that, then you can never be sure how many moles it is. And then you could never, like, have actually accurate calculations."

The Student 4, through their response, indicated that scientific instruments have contributed to the advancement of science by providing accurate, quantitative measurements, and ultimately enabling accurate calculations. Thus, this response again signifies the common theme that students view instruments as a way to enhance data accuracy and measurement.

On the other hand, three students, including Students 6 and 10, acknowledged the role of instruments in scientific progression differently:

> Student 6: “[…] They can't contribute to the advancement of science because they, they play a critical role in the existence of science itself. Science wouldn't exist if instruments couldn't exist. I mean, it's the other way. You can have the instruments, and you can't have, and you might not have science. But you can't have science and not have instruments.”

> Student 10: “Definitely. I mean, people have discovered or in during the earlier days, people just used to take such a long period of time to discover something. Like, when we study about atoms or something subatomic particles, we know that probably Rutherford's experiment was really long and complicated. And he might have taken years to get that done. [...] So it has the, I mean, it was like a bridge, like all these instruments are like a bridge that, you know, they just provide, like a shortcut or something. They're like catalyst.”

Thus, while perhaps a small fraction of students, there are students in general chemistry who can articulate a substantial understanding of the role of instruments in the progression of science. Student 6 believed science could not exist without instruments, which was a view expressed by no other interviewee throughout the interview processes. This response provides a reason for optimism that more students can be reached to have deeper understanding of the central role instruments have had in scientific advancement, and why we should try to advance student understanding of NOS and instruments. Rather than stressing the data output or the “numbers” aspect of instrumentation in chemistry courses, guiding students to grasp the wider view of instruments, more specifically, how scientific observations and inferences are made possible through instruments, could be a valuable pedagogical approach.

An important motivation for this study was to ascertain what students perceive about the role of scientific instruments to determine how to teach the key aspect that instruments allow us to observe natural phenomena. Recognizing that science is a socially embedded practice, and that chemical reactions occur all around us whether we are aware of them or not, can students be guided to better understand how observations advance both science and scientific thinking? Cooking and baking are some of the commonly encountered platforms where chemical reactions occur, and many students recognized this during interviews. To push further, and to understand how mindful students were of the chemical observations outside of science, participants were shown a short video of a souffle rising as it bakes in the oven. Following the video, students were asked whether there is any difference in how they make observations between real life situations (i.e., in the video) and lab settings.

All students, to some degree, agreed that observations are different in these two situations. The most common difference was the degree of observational details they may pay attention to. Students answered that they purposefully make detailed notes and observations in lab for experimental purposes, whereas any observations they make in life would not be nearly as detailed. It was also emphasized that more detailed quantitative observations would be common in lab, whereas qualitative observations are enough for real-life situations. This was yet another example showing that students are focused on the quantitative aspect of chemistry in laboratory.

Along with the level of detail, most participants also mentioned that they often do not think about chemistry outside of the laboratory context, separating life experiences from the laboratory or scientific experiences. An example response for this reasoning can be seen in Student 9's quote:

Student 9: "I'd say it is probably different, because you're not thinking about it, like baking, most people don't think about how it's going to produce a cake, or chemically what's going to happen. Um...you kind of just go on through the day, you just like mix your cake, you bake it, and cool, you have a cake and you are going to eat it. Um, in chemistry you are specifically thinking about how things are going to react and why they're going to react. How does like, how do the reactants turn into the products, what's required to make it happen."

Among the participants, only three students did not suggest there were significant differences between the two contexts, and these students all indicated that they often think about chemistry behind phenomena they come across in life, such as baking, without being prompted to do so. The responses here show a glimpse of the perspectives held by most student participants, that there exists a separation between science and life rather than thinking of science as socially embedded practice.

Views on Data Evaluation

While students may be susceptible to overlooking the role of instruments in the way science progresses, they are likely to recognize the role of data. This concept was demonstrated by the results noted earlier that measurement and accuracy were common concepts of instruments mentioned by the students. As one of the emphases of learning within the psychomotor domain ("doing")[44] in typical general chemistry laboratory courses is collecting data, one of the ideas the authors wished to explore through the project was how students treat the data that they obtain from instruments. The interview participants were asked whether they evaluate their data in lab, and if so, how, as well as why or why not they think it is important to evaluate the data. Roughly 2/3 of the students said they evaluate their data, whereas the other 1/3 indicated they only do so occasionally. Comments from students tended to show an instructor effect, based on the role of the teaching assistant (TA) in the laboratory. Of the 9 students who indicated they engage in data evaluation, 2 students specifically said they do so as a class with their TAs. Student 14 talked about forming a habit of engaging in data evaluation over time, owing to the TA's effort of leading a discussion after each experiment:

Student 14: "My TA […] leads a postlab discussion every time, where we talk about what happened, and if everyone got that result, and why it happened. And then, if you didn't get that result, why that didn't happen. So, errors and things like that. So, I guess her doing that kind of got me in the habit of thinking that way."

Student 14 specifically indicated that evaluating data was not part of their scientific practice before this course. Thus, Student 14 serves as an example of students in chemistry courses may require explicit instructions or demonstration of why such data were collected and what can be inferred from them, rather than the emphasis on the action of collecting data.

In addition, time constraints appear to be an element that affects students' behaviors (i.e., frequency of data evaluation) in laboratory courses. These ideas echo the findings of previous reports studying the importance of pre-laboratory preparation and the effects of numerous pre-laboratory activities have been studied.[63-67] Furthermore, feeling a constraint for time in laboratory has been reported in other studies as an affective factor that influences students' behaviors.[46,68,69]

It is important to note that while all interviewees recognized data evaluation as an important practice, not all students participated in it for every experiment. As mentioned previously, one third of the interviewees indicated engaging in data evaluation only sometimes, and a few with the explicit guidance of their TAs. Additionally, some students emphasized correctness of the data for writing correct lab reports as a reason for engaging in data evaluation practice. This observation indicates possible shortcomings of current general chemistry laboratory courses: emphasis on the correctness of data, leading to underemphasizing the process of making observations with instruments and the inference making processes that ultimately form scientific knowledge, as well as the differing effects TAs or instructors can have on students' scientific practices.

Views on Learning about Instruments

When it comes to learning, how students feel is deeply connected to how they think and behave.[45,46,70,71] The initial part of this study focused on cognitive (i.e., students' views on instruments) and psychomotor (i.e., how students evaluate data) domains of instrument learning in chemistry laboratory, but it is important to keep in mind that meaningful learning requires an engagement of three domains: cognitive, psychomotor, and affective.[45] To investigate students' affective states towards instrumentation, questions about feelings and motivation were asked. Mixed feelings were expressed by students about how they feel towards instrument learning, and these mixed feelings can be seen in Student 2 and 7's responses:

Student 2: "I mean, I like using them, when I know how, but like, learning how to use them is like pretty boring."

Student 7: "Um, kind of mixed. […] It's kind of difficult to figure out exactly how they work. But once I get it, it makes the experiments a lot easier. […] I'd say, I'm mostly, I'm curious because I know how helpful they can be. And also, a little apprehensive that I'm gonna mess it up or break something."

While a few students voiced negative emotions, approximately 2/3 of the interviewees held positive feelings about instrument learning for various reasons, including the usefulness of knowledge for future and simply wanting to acquire more knowledge. The following quotes from Students 1 and 8 show both sides of the reasoning:

Student 1: "Oh, yeah, yeah, I think those are really cool. […] I think it'd be useful, you know, anytime down the road, we may have to do titration for some reason or something like that."

Student 8: "Um, I think that there's always something new to learn about, and I think it is helpful to expand your knowledge of different instruments, whether you, your focus is in science or not. I think it's just useful for the development of society and you as a person."

Negative affective states have been observed with students working in laboratories[46,68] for reasons including fear of using equipment.[69] For the participants in this study, feelings toward instrument learning were mostly positive, but it was of interest to analyze how students react to a situation where they are starting to learn about a new instrument. In this situation, 8 out of 14 students expressed negative feelings such as being anxious and scared. Reasons ranged from feeling pressed for time to being afraid of breaking the instrument.

> Student 5: “I get a little anxious that I'm going to do something wrong with it. So I definitely have found myself reading the lab information over and over, because I want to make sure that I don't miss any little detail. So definitely, like, over preparing myself before I use it, because I don't want to break it or something like that or use it incorrectly.”

Student 5’s response, again, shines a light on the impact that the level of preparation could have on how students feel about in-lab activities. This may be especially true when students perceive they have a limited amount of time to complete experiments. The response from Student 7 illustrates the student perception of the time-constricted nature of lab learning:

> Student 7: “Uh, nervous. Yeah, especially because, like in a lot of labs, things are kind of time sensitive, so you don't really have a lot of time to kind of work and figure out how things work.”

The perception of time intensity in the laboratory and the importance of preparation noted here were also mentioned by some participants regarding data evaluation. Providing an ample amount of information on not just procedures, but also on instrumentation, may be a helpful method of reducing the in-lab pressure, whether it is for time or misuse of instruments.

Given that both positive and negative feelings were present for laboratory learning, a question arises as to what motivates students to overcome the negative feelings in instrument learning. For most students, the source of motivation to learn about instruments in lab was related to their performance in the course. Performance-driven desire to learn in lab has been demonstrated in other studies,[68,72] thus it is unsurprising that students’ motivation to learn about instruments was based on the same goal. The next most commonly mentioned factor was the potential usefulness of the knowledge in future careers. The least popular source of motivation was an inherent desire to know, in other words, intrinsic motivation. Three students indicated that the motivation to learn comes from wanting to know and understand the process. For example, Student 6 said:

Student 6: "[...] what motivates me personally, […] chemistry is everything. You know, it's the manipulation of the world around us, it's one of its most fundamental levels. Like, that's motive, that should be motivation enough to just do it, and learn about it. It just makes sense to me."

As observed in chemistry lecture courses, intrinsic motivation was not a common purpose behind learning about instruments.[73-76] External sources of motivation, such as course grades or potential use of the knowledge in the future, were overwhelmingly common within the interviewees.

Whether students expressed positive, negative, or mixed feelings about instrument learning and regardless of their source of motivation, all but one interviewee acknowledged the importance of learning to various degrees ranging from slightly to very important. For many students, the importance arose from the expectations of future usefulness of the knowledge and course performance reasons. Major area of study was also related to how important they thought instrument learning was to them. Student 4, who was a chemical engineering major, said:

Student 4: "To me, I think is pretty important just because I'm going to be using a lot of those things in the future. And they'll be beneficial to me. But to someone who's like a business major, it wouldn't be as important."

There were, however, examples of students with more expansive views about the value of knowledge about instruments, such as this quote from Student 13 on the interconnected nature of science and society:

Student 13: "I think it's really important. Because if we didn't take the time to learn how things are done and learned about how society is conducted, like, you personally would never grow, because you can, it's like, because I mean, there's scientists and there always will be and people that are professionals that like, whether they're chem professors or people that get a degree in Chemistry or Chemical Engineering that will continue to always for the advancement of chemistry or whatever craft it is. You can always rely on those people. But at the same time, I think as people, we can't just expect others to do everything for us. And so I think it's really important for us to take the time to grow, and to learn about how things are done."

Generally, students in this interview study conceptualized the role of scientific instruments in relation to their academic context, oftentimes relating back to the laboratory courses and reciting instruments' capacity to measure a property. Some students were able to readily extend the concept of instruments to the real-world settings, acknowledging the important social and cultural roles (sociocultural-embedded NOS) scientific instruments might hold. However, many students struggled to grasp the interconnected nature of scientific instruments and society.

Those students who thought of instruments exclusively as means to obtain accurate or precise measurements for experimental reasons, found motivation to learn instrumentation largely from the usefulness of the instrumental knowledge in future courses or careers. The small number of students who made deeper connections between the instruments and society were more intrinsically interested to learn how they operate and how they fit into the real-world settings. These students also acknowledged the value of their ability to make experimental measurements.

Discussion and Implications

The first research question of this study was: How do general chemistry students conceptualize the role of scientific instruments? As observed during the interviews, students possessed a wide range of understanding about how and where instruments are used. Ultimately, a majority of students showed fragmented knowledge of the range of uses of scientific instruments (empirical and inferential NOS) or how instruments were connected to life (sociocultural-embedded NOS). For many students, only commonly known and used measuring tools such as a thermometer or ruler are readily recognized as instruments. Some students were more readily able to provide examples of instruments that were not directly related to their laboratory courses. Additionally, a select few students presented advanced awareness of the instruments' usage inside and outside the science as well as their interconnected nature, demonstrating more nuanced understanding of the socially and culturally embedded nature of science.

Interviews also revealed the presence of an instructor (TA) effect, particularly related to how students perceive data evaluation and the level of interest students showed toward instrumentation. Considering that general chemistry students may possess incomplete knowledge of scientific processes, laboratory TAs leading each lab section can greatly affect the way students think and feel about instruments. This observation is consistent with expectations of near-peer teaching/learning.[77]

Overall, the understanding of scientific instruments and the interest of general chemistry students in experimental science appeared to be connected (RQ2). Students with deeper understanding of the role of instruments in science and society, incorporating more ideas of NOS in their responses, expressed more intrinsic interest in learning about instruments. That is, those students articulated that learning instrumentation is not only useful for their future studies or work, but that it helps them to better understand how society has advanced with science. The latter view was held by only a few students in this study.

A student perception of the disconnect between chemistry lecture and laboratory courses were also observed in this study, where some students perceived instruments were only for the laboratory course whereas concepts and math were for the lecture. These observations point to the tendency of students to compartmentalize learning, which may be addressed with explicit instruction about how instrumentation functions and connecting those ideas to relevant topics (i.e., providing opportunities to see the sociocultural-embedded NOS) that enhance student's desire to learn. These areas of improvement likely need to be advanced both in chemistry laboratory and lecture courses.

Chemistry curricula may provide students with more comprehensive views of the nature of science and how scientific understanding is advanced by utilizing the history and the role of instruments in science. In addition, integrating the sociocultural-embedded aspects of science into chemistry curricula can enhance students' interest in the subject, as well as increase their awareness of the nature of science. Ultimately, scientific knowledge is constructed through observations and inferences made possible with instruments, and science cannot be separated from society we live in. Introducing students to a more comprehensive perspective of science and its practice can be based on the nature of science notions. Such instruction could be an important step towards nurturing students towards advanced scientific literacy.

Limitations

The nature of interview based qualitative research presents limitations that are present in this work. It is not possible to infer proportions of the general chemistry student sample overall that may hold any of the observed ideas about laboratory instrumentation based on the number of student participants that express a particular view. Thus, no conclusions are drawn from this study about how many or how few students understand laboratory instruments in a particular way. Rather, the interview data and its analysis has identified a range of ideas held by students, and that range is likely, but not certain, to be in a larger sample of students.

Recruiting students for the interviews from a single institution that has a specific level of instrumentation use in laboratory settings may also influence the observations made through the interviews. Students from schools with far more, or far fewer, instrument dependent laboratory experiences may provide additional information that is not uncovered in this work.

Conclusion

The current study utilized a semi-structured interview to explore how general chemistry students view instruments in terms of their roles in science, outside of science, and how these ideas are connected. While many students understood instruments exclusively through the lens of current or previous chemistry courses, it was noted that a few students were able to make deeper connections between science and life through instruments. Students' views on the value of learning about instruments were also assessed through the interview. Many students held a positive view on learning about instruments for various reasons such as the usefulness of knowledge and relevancy. The recurring theme of relevancy from the interviews provides evidence that the nature of science ideas can be an important instructional method in chemistry education.

Associated Content

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.]

Interview Questions and Codebook (DOCX)

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