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Students' Understanding of the Nature of Science in the Context of an Undergraduate Chemistry Laboratory

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ABSTRACT

This study focused on exploring and evaluating students' views of the Nature of Science in the context of undergraduate chemistry laboratory. Thirty-six undergraduate students doing a laboratory course in upper division physical chemistry were assessed using an open-ended instrument and assessment criteria that categorise them in three levels of understanding. Results revealed that in general, the undergraduate students have transitional views of the nature of science, a level between naïve and informed views. The findings led to a substantiated argument for incorporating the nature of science in undergraduate science curricula.

Keywords: nature of science, laboratory education, undergraduate chemistry

Introduction

Although laboratory work is often regarded as an indispensable part of modern science education, it was not until the latter 19th century that individual laboratory work became a common phenomenon in science courses (Bradley, 1968). To date, science education, particularly on tertiary level, is thriving with both practitioners and researchers taking a closer look at laboratories in order to make the most out of its distinctive qualities and characters. Laboratory courses are offered to students as contrived learning experiences in which they interact with materials (Hofstein & Lunetta, 1982), often in a concerted fashion with lectures and tutorials. The courses vary in structures as specified by the course designers and instructors, but they typically involve a central performance phase *in* the laboratory, aside from phases of planning and preparation, data analysis and interpretation. Despite widespread and tacit acceptance (Sweeney & Paradis, 2004) of the role of laboratory work in science curricula, its essential value has been placed under scrutiny. For example, Hodson (1992) and Kirschner (1992) argue that we need to re-examine the way laboratory education has been assumed, practiced, and studied.

One of the contestable aspects of college laboratory education is the extent to which laboratory work provides avenues for learning about the nature of science (NoS). The understanding of NoS is increasingly becoming an important science learning outcome, particularly for preservice science teachers and science majors (Schussler et al., 2013). The caveat is, NoS concepts are not easy to measure and, indeed, also difficult to define. For this reason, most studies of nature of science use qualitative instruments (Agustian, 2019).

According to McComas (2002), many science educators claimed to have taught NoS in their practice. However, data analyses scarcely revealed explicit reference to NoS in their planning and instruction (Abd-El-Khalick et al., 1998). The positivist view of science from the 19th century still informed much classroom practice and pervaded most available curriculum materials (DeBoer, 1991). Even more dreary, for most science students, a description of NoS, if any, is relegated to a few paragraphs at the beginning of the textbook quickly glossed over in favour of the facts and concepts that cram the remainder of the book. And the ideas put forth in textbooks concerning the nature of science are almost universally incorrect, simplistic, or incomplete (Bentley & Garrison, 1991).

Five decades after the prolific studies on curriculum reform in science education in the 1960s (*e.g.*, Carey & Stauss, 1968, 1970; Cooley & Klopfer, 1961, 1963; Kimball, 1968; Welch & Walberg, 1968), the literature unfortunately still shows that students and teachers have an inadequate epistemological understanding of the nature of science (Abd-El-Khalick, 2012; Niaz, 2016). According to Abd-El-Khalick (2012), the current state of affairs is caused by a host of factors, including the complexities associated with bringing about significant and systemic change to the beliefs and practices inherent to science education. Making headway with an especially challenging domain, such as teaching and learning about NoS, necessitates synergistic, long-term research and development efforts. Also, the domain of NoS largely remains a field of scholarship for non-practicing scientists. The overwhelming majority of practicing scientists do not have active research programmes that address epistemology of science (Abd-El-Khalick, 2012).

This article explores undergraduate students' view of NoS in the context of science laboratory. I will begin with a critical literature analysis of the role of laboratory in chemistry education, followed by argumentation for the nature of science in laboratory education. Herein some pedagogical and philosophical considerations will be weighed against the recent and current trend in science education.

Arguments for Laboratory Education

The case for laboratory education has to be established for a few compelling reasons. Running a teaching laboratory is not an easy task. It entails a high cost of facilities, staffing, equipment and supplies. Furthermore, most laboratory work also takes up considerably plenty of time on the side of both students and instructors. It is not an exaggeration that laboratory instructors are really expected to assign highest priority to the design of quality laboratory (Fife, 1968). But why exactly is laboratory education so important? Which ideals are to be strived for? Are they actually accomplished, or even attainable in the first place? The following arguments are presented in an attempt to shed light on these issues.

Science laboratory is a multifaceted enterprise that ideally serves a purpose of teaching specific practical skills, affording students a phenomenal experience (Kirschner, 1992), nurturing scientific thinking and intellectual development, providing an opportunity for social relationships, and catering for students' affective needs. But most of all, it is an excellent context for engaging in activities that give students an insight into the nature of science, the very core of science education that is ironically often overlooked or, in too many cases, even dismissed. In the following subsections, these arguments will be elaborated.

Specific Practical Skills

Kirschner (1992) argues that because one of the goals of university science education is preparing the students for independent scientific work or the application of scientific methods, laboratory education should be directed towards the specific subskills needed. Some of the skills that are considered relevant and important in such context are planning and execution skills (Kirschner, 1992), manipulation skills (Bradley, 1968), observation skills, investigation skills, and reporting skills (Hofstein & Lunetta, 1982). Seery and colleagues (2018) also uphold application of these skills to unknown situation.

Scientific Reasoning

Laboratory education is important because it directs students to think scientifically. Hofstein and Lunetta (1982) describe scientific thinking as an ability to recognise problems, understand experimental methods, organise and interpret data, test hypotheses, and make generalisations. The primary concern of science education is the pursuit of knowledge and laboratory should provide an access to knowledge and its relationships (Kirschner, 1992). In order to do this, students must be given opportunities to plan and conduct logical procedures and strategies, demonstrate the implications of scientific theories and laws, ask good questions and question the taken-for-granted.

There is a growing evidence that inquiry-based laboratory activities in particular could enhance the attainment of scientific reasoning. Newer laboratory curricula, such as inquiry-, problem-, and research-based laboratories, emphasise the development of higher cognitive skills. In these curricula, laboratory acquires a central role of science learning process, not merely a place for verifying concepts. Undoubtedly, the extent to which these curricula serve their purpose is open to investigation, but knowledge in this area is developing. See for example Rudd II et al. (2001), Hofstein et al. (2005), French and Russell (2006), Kelly and Finlayson (2007), Zoller and Pushkin (2007), and Weaver et al. (2008).

Creativity and Problem Solving

In his elaborate work on creativity, Weisberg (2006) illustrates creativity in science with the discovery of the double helix structure of DNA:

> More than simple observation is involved in scientific research. Scientists often draw conclusions from very indirect evidence, so their knowledge and comprehension are critical to their success. This is a step away from the notion of science as the simple discovery and study of objective facts. One could say that the helical shape of the DNA molecule was not an objective fact, in the sense that it was not sitting there to be observed. One might go even further and say that it was a "created fact." (p. 19)

Laboratory provides possible avenues for students to be creative with experimental designs, revision of methods and enacted procedures, data interpretation, and even drawing conclusions. When done properly, it gives opportunities for combining ideas, techniques, or approaches in a new way. More open-ended laboratory activities such as those mentioned in the previous argument might be a great context to develop creative thinking (Hofstein & Lunetta, 1982).

Laboratory work is also a relevant context for learning to apply an academic approach to a problem, in the form of an investigation. Kirschner (1992) argues that university science students are essentially scientists in training, so they have to familiarise themselves with the way scientists operate. This is characterised by carefully examining a situation and acknowledging that there is actually a problem, defining the problem to be solved, specifying the most suitable strategy, solving the actual problem, and evaluating the results to see if the problem has been solved. In the science laboratory, students can develop competence in solving a problem (Galloway et al., 2016). With that in mind, Kirschner proposes a model for academic problem solving, as shown in Figure *1*.

Social Relationships

Laboratory is not only a place for conducting scientific experiments, it also provides an opportunity for social interaction, in which discussions are encouraged (French & Russell, 2006). Therefore, it has a potential to enhance constructive social relationships defined by factors such as cohesiveness, task orientation, goal direction, and democracy (Hofstein et al., 2001). Hofstein and colleagues argue that much of this potential is attributed to the less formal nature of social interaction in the laboratory as opposed to, for example, a lecture situation. It also promotes team working (Edward, 2002), peer teaching and a positive learning environment.

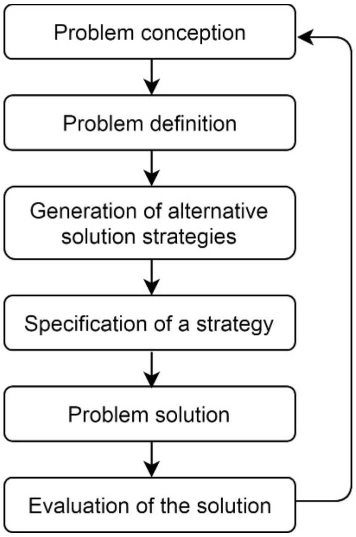

Figure 1. Kirschner's model for academic problem solving.

Affective Domain

According to Johnstone and Al-Shuaili (2001), affective aims in science laboratory can be divided into two main categories: attitudes to science and scientific attitudes. The former constitutes general affective aspects such as confidence, motivation, interest, enjoyment, and satisfaction. The latter refers to traits and ways of thinking pertinent to science, such as open- and critical-mindedness, scepticism, curiosity (Zion & Sadeh, 2007), and intellectual honesty (Aiken Jr & Aiken, 1969).

Albeit often stated in curriculum goals, the affective dimension of laboratory education is not much researched (Agustian & Seery, 2017; Galloway et al., 2016). Similarly, Hofstein and Lunetta (2004) assert the following:

> The failure to examine effects of various … science experiences on students' attitudes is unfortunate since experiences that promote positive attitudes could have very beneficial effects on interest and learning. The failure to gather such data is especially unfortunate in a time when many are expressing increasing concerns about the need for empowerment of women and underrepresented minority people in pure and applied science fields.

This is arguably an even more compelling case for addressing the affective dimension of science education in the present time, when attitudes towards science and scientific attitudes ironically decline whilst access to scientific information is wider than ever before. Edward (2002), for example, concedes that published analyses of laboratory activities report low motivation among participants, with students finding chemistry irrelevant and boring. This, in turn, makes us 'swing away from science' (Osborne et al., 2003, p. 1050). On the other hand, Wong and Fraser (1995) found that chemistry laboratory classes which display favourable levels of learning environment factors such as student cohesiveness and open-endedness promote student enjoyment of their chemistry lessons.

Understanding of the Nature of Science

As mentioned previously, the role of laboratory education that addresses the nature of science (NoS) is often overlooked and even worse, dismissed. In a systematic review of six decades of research development in the nature of science in science and laboratory education (Agustian, 2019), it was found that only about one fifth of the scholarly literature in the nature of science addresses laboratory as a setting of investigation and intervention. This raises even more concern considering there is still lack of attention to NoS in practice, whilst it is often lauded as a goal of science education (*e.g.*, Abd-El-Khalick & Lederman, 2000; Goff et al., 2012; Marchlewicz & Wink, 2011; Martin-Dunlop, 2013; Ross et al., 2013). I will argue further about this aspect in the following section.

Arguments for the Nature of Science in Laboratory Education

Science has a pervasive but often subtle, impact on virtually every aspect of modern life, both from the technology that flows from it and the profound philosophical implications arising from its ideas (McComas, 2002). For example, the latest news on the first ever image of black hole captured by more than 200 international scientists (National Science Foundation, 2019), immediately caught public attention and sparked discussions about some of the most interesting and elusive aspects of astrophysics. However, despite this seemingly worldwide effect, few individuals have an even elementary understanding of how the scientific enterprise that led to the discovery operates. This lack of understanding is potentially harmful, particularly in societies where citizens have a voice in science funding decisions, evaluating policy matters and weighing scientific evidence provided in legal proceedings. In the age where anti-vaccination movement and flat earth believers ironically thrive in the abundance of information, teaching about NoS is essential to a science education that wishes to prepare not only future scientists, but also cultured and informed citizens. Similarly, Duschl and Grandy (2013) contend that science learning and teaching ought to be grounded in epistemological, sociocultural structures, and practices.

Literature strongly suggests that NoS understanding seems to be a cognitive learning outcome that needs to be planned and explicit in order to enhance students' understanding effectively (*e.g.*, Abd-El-Khalick et al., 1998; Burgin et al., 2015; Demirdöğen et al., 2015; Scharmann et al., 2005; Schussler et al., 2013; Schwartz et al., 2004). Nevertheless, the science laboratory as a context for teaching NoS, especially in an undergraduate science major setting, has almost been absent in published research reports (Yacoubian & BouJaoude, 2010). This study was conducted largely upon this rationale. There are at least three arguments for teaching NoS in the context of science laboratory, which will be elaborated in the following subsections.

Ontological Arguments

Ontology is a philosophical study of the nature of being, existence and reality. Some of philosophical problems pertaining to the existence of a god, for example, are problems in ontology. It concerns whether or not an entity exists, but also encompasses problems about the features of and relations between existing entities. In science laboratory, these are often the problems of theories and concepts: how theories came to exist and how scientific concepts relate to one another. Nersessian (1989) argues that the ontology of a scientific theory determines the entities it claims to be about, and that change in scientific theories, such as theories of atom, is actually the history of changes in ontology.

In the early development of science, there have been disagreements between rationalists (the likes of René Descartes, Baruch Spinoza, and Gottfried Leibniz) and empiricists (the likes of Francis Bacon, John Locke, and David Hume) on the ontological status of scientific theories and the entities they often postulate. The debates led to, among others, a positivist view of science. One vestige of logical positivism is the belief that scientific knowledge connects directly with reality, unencumbered by the vulgarity of human imagination, dogma or judgements. This ontological view is often associated with the idea that science strives to find absolute truth, and does so independently of the investigator's psychological and social milieu. Such naive realism has been challenged by other philosophical positions (*e.g.*, Aikenhead, 1987; Bickhard et al., 1985; Kuhn, 1962). Abd-El-Khalick

(2012) argues that disagreements about what NoS entails are 'relevant and need to be meaningfully addressed in any framework that aims to guide synergistic research and development efforts' (pp. 68).

Correspondingly, ontological assumptions lie in the heart of science conceptual network. When one of those concepts changes, it will reverberate throughout the network. McComas et al. (1998) maintain that when common sense ontology changes into a scientific ontology, abstract entities need to be constructed. As an illustration, Newtonian mechanics initially existed only in mental models, upon observation of the natural world. Changes from observational accounts to mathematical equations necessitate transforming a concrete into an abstract representation. In laboratory education, this is often the problem that lingers from one curriculum reform to another. How can we best facilitate the transformation with an effective instruction in abstraction techniques so that students can build the requisite scientific ontologies?

Evidence suggests that knowledge of NoS assists students in learning science content. For example Songer and Linn (1991) illustrated the importance of students having dynamic rather than static views of science in developing a conceptual understanding of topics such as thermodynamics. The static view of science is the idea that science is a group of facts that are best memorised. The dynamic view of science posits that scientific knowledge is tentative, and the best way to understand this knowledge is by understanding what scientific ideas mean and how they are related. Although the authors did not address the mixed view, they did find that students with dynamic views of science acquired a more integrated understanding of thermodynamics than those with static views.

Epistemological Arguments

In his case for integrating NoS into science education, Taber (2016) argues that science education should be aimed at *understanding* of scientific concepts or ideas but not *belief* in them. He exemplifies his argument by resistance among students and teachers against the theory of evolution. Students bring their own presuppositions about the world into the classroom. When personal and cultural values are in conflict with scientific ideas, it is utterly counter-productive to teach those ideas in a dogmatic manner, so as students believe in them.

In the pursuit of knowledge, science is a dynamic, ongoing, and process-oriented activity rather than a static accumulation of information (Kimball, 1968). The tentative nature of scientific knowledge is therefore essential to be taught explicitly, so that students do not feel threatened and forced to reject deeply held faith that contradicts the new information. In the context of laboratory education, scientific knowledge encapsulated in multifarious concepts also calls for a similar approach. Cleminson (1990) summarised the way knowledge develops:

- Knowledge, concepts and theories about the physical world are personally constructed and their status is provisional.
- We use these personally constructed views as our personal theoretical lenses and determine what counts as an observation and what counts as an inference.
- Learning new scientific concepts requires a creative act of the imagination, rather than merely the utilisation of established methods of scientific inquiry.
- Such learning process is problematic and never easy, as we might have to abandon deeply held knowledge.
- Whether or not related to formal science, our conceptions of the physical world are subjective to us.

When all these are taken into considerations in laboratory curriculum design, students are expected to have a stronger grip on the epistemological stature of scientific knowledge and concepts behind the experiments they conduct in the laboratory. Accordingly, understanding how science operates is imperative for evaluating the strengths and limitations of science, as well as the value of different types of scientific knowledge (McComas, 2002). Uninformed statements such as "Evolution is *just* a theory" or "Theories can be proven and, as such, can become laws" stem from misconceptions about the role of law, theory, and model in science and what they mean.

Due to the rapid development of science, some of the scientific knowledge a person learns in school will be substantially modified during their adult life. However, the nature of science as a cultural activity that produces, evaluates, develops and sometimes demotes, scientific knowledge, does not change. Taber (2017) argues that wrong perception of science as a body of literal truths leads to unduly questioning of the entire fields of knowledge when single facts are revised. He upholds the view that the tentativeness of scientific knowledge should be seen as a strength rather than a weakness, as science keeps correcting and refining itself. In that sense, laboratory work in undergraduate science should provide avenues for learning about this epistemological aspect.

Pedagogical Arguments

The persistence of students' naïve ideas in science suggests that instructors could use the historical development of scientific concepts to help illuminate the conceptual journey students must make away from their own naive misconceptions. In other words, teachers' interest in NoS could assist in understanding the psychology of students' learning (McComas, 2002). Matthews (1994) has argued for the inclusion of NoS courses in science teacher education programs. The examples he provided demonstrates that a firm grounding in the nature of science is likely to enhance teachers' ability to implement conceptual change models of instruction. Studying the process of historical conceptual development in science may shed some light on individual cognitive development (Wandersee, 1986).

Within science education, changes in our understandings of what is science—the nature of science—have influenced our understandings of what's involved in learning and doing science. Conversely, our understandings of what's involved in learning and doing science have influenced our understandings about the nature of science (Duschl & Grandy, 2013). For example, some of the resistance to conceptual change theory among classroom teachers arises from the mistaken notion that knowledge of the natural world is completely objective—existing independently of the searching individual. This view of science gives the impression that learning is a fairly straightforward process of replacing what is known with that which the scientific community has discovered is right (McComas, 2002). Teachers who viewed chemistry as a stable body of concepts, principles, and theories, had difficulty finishing the course because they attempted to teach everything as fundamental.

Taber and Akpan (2016) contend that a good science curriculum needs to not only teach some science, but also teach about science. There needs to be a balance between teaching the products or outcomes of science and teaching about the processes of science; between cognitive, epistemic, and social aspects of science (see also, Erduran & Dagher, 2014). The challenge is, shifting from an indirect teaching of the nature of science to a direct, explicit pedagogy of science required us to redesign the existing curriculum (Goff et al., 2012). Ideas from the interdisciplinary research communities of learning sciences and science studies extend our understandings of science learning, science practices, scientific knowledge, and scientific discourse (Duschl & Grandy, 2013).

From a pedagogical viewpoint, the affective learning domain can also benefit from NoS instruction in the laboratory. A sensitivity to the development of scientific knowledge may also make science itself and science education more interesting. According to Tobias (1990), a number of potential university science students lament that science classes ignore the historical, philosophical, and sociological foundations of science. Incorporating the nature of science while teaching science content humanises the sciences and conveys a great adventure rather than memorizing trivial outcomes or concepts (McComas, 2002).

Methodology

The qualitative data in this study is analysed through a hermeneutic phenomenology lens, which is an approach to exploring the conscious experience of phenomena from the viewpoint of individuals (Coles & McGrath, 2010). The father of phenomenology, Husserl (1970), states that phenomenology is more interested in the process of knowing and understanding, rather than finding hard, external reality. It questions the obvious and transforms it into something intelligible, through exploration, examination, elaboration, and explanation of meanings. Schutz (1967) maintains that in order to analyse those meanings, the world of experience (*Erfahrungswelt*) is contextualised as a total structure built with different arrangements and identifying characteristics.

In juxtaposition to the conventional natural science research, a hermeneutic researcher uses a different approach to data, methods and theory compared to a researcher operating from within a positivist framework, which typifies a conventional natural science researcher. In hermeneutic research such as phenomenology, accounts of social reality held by the research participants are prioritised (Bunce & Cole, 2008; Scott & Usher, 1996). To some extent, this research gives them a voice. Intentionality and subjective meanings are valued as much as hard, numerical data.

Hermeneutic phenomenology has a potential as a research framework for discerning learning experiences in laboratory (Casey, 2007; Gatlin, 2009, 2014). It is because learning experiences encompass not only cognitive dimension, but also affective and psychomotor. The complexity of psychological and educational domains is often dismissed by researchers operating in the hyperrational domain (Kincheloe & Berry, 2004). They further argue that human beings do not act in automatic response to physical forces such as atmospheric pressure. Rather, they move within intentional frames of mind that at times lead to unexpected or irrational behaviours. This phenomenological form of information is necessitated by particular epistemological and ontological conditions rarely recognised in monological forms of empirical research.

Context and Participants

This study was conducted in the physical chemistry laboratory at a Scottish university, which was a part of an undergraduate physical chemistry course. It is part of a research project on students' learning experience in the chemistry laboratory. The whole project was set to be conducted from September 2016 until December 2018, involving third-year students as participants. This paper reports findings primarily from the second half of the project.

The third-year physical chemistry laboratory course is aimed to give students further practical experience of techniques; help them develop the skills to design, plan and carry out their own experiments; teach them to critically appraise the validity of data and work to high professional standards of safety and practice; and further develop their scientific writing skills. In third year physical chemistry, students attend for 6 h a week with an assumption that they will spend 6 h a week on processing and analysis in preparation for their report. In the course of three years that this research was conducted, there has been a structural change in the Year 3 physical chemistry laboratory curriculum, as described in Seery et al. (2018). Prior to the change, students completed four expository experiments followed by two weeks of investigative inquiry, amounting to a total of six weeks of laboratory rotation. In the new structure, an expository experiment (labelled as Part 1), is immediately appended with an investigative inquiry based on Part 1 (labelled as Part 2), so that students have sufficient time to study the chemistry behind the experiments in more detail and gradually conduct more inquiry to prepare them for more advanced stages in their laboratory course.

Organisation of Laboratory Instruction

The existing pre-laboratory resources at the physical chemistry laboratory are accessible on an electronic platform called eLM (electronic Lab Manual). Depending on the experiment, they usually consist of a pre-laboratory video on the underlying theory, a pre-laboratory video on relevant experimental skills, a post-laboratory video on data analysis, and an online discussion forum. A printed out laboratory manual is given as a reference, in which a few questions related to the experiment are to be answered and submitted prior to laboratory work. Anyone who fails to do so is not allowed to do the experiment.

The experiments are designed to be easily completed within three hours. Usually students work in pairs. The molecular modelling is completed in students' own time outside formal laboratory periods. The investigation takes up four practical sessions, including one session on introduction. All reports are written and submitted individually. Demonstrators are within reach at all times for any queries regarding the experiment. Albeit they do not give brief pre-laboratory lecture, their play a role as a supervisor. The class is divided into seven groups, each of which is formally assigned to two 3-hour sessions per week. The first session is for the experiment and the second is a write-up session. The write-up session is also supervised by demonstrators.

Research Instruments and Measures

Views of Nature of Science

The evaluation instrument Views of Nature of Science (VNoS) was developed by Lederman's research group (Bell et al., 2003; Lederman et al., 2002; Schwartz et al., 2004). It was designed mainly on a rationale that previous convergent instruments were all based on forced-choice items such as Likert-scale, agreement/disagreement, or multiple choice. See for example, Billeh and Hasan (1975), Cooley and Klopfer (1961), and Rubba and Andersen (1978). Resulted in three forms, VNoS development addressed issues regarding validity and the usefulness of previous instruments, as well as developers' biases related to their NoS views.

In this study, an adapted version of VNoS Form B was used to evaluate undergraduate students' views of the nature of science in the laboratory. The instrument consists of seven open-ended statements that correspond with seven aspects of the nature of science, *i.e.* empirical nature of scientific knowledge, inference and observation in science, tentative nature of scientific knowledge, scientific theories and laws, creativity and imagination in science, philosophical subjectivity in science, and social and cultural embeddedness of science. A redefinition of these aspects in light of the current philosophical has been debated elsewhere (Agustian, 2019).

Semi-structured Student Interviews

In order to explore and evaluate students' understanding of the nature of science, semi-structured interviews were conducted. The interviews were used as a primary source of data on a rationale that constructs belonging to the epistemic domain of learning are better analysed through interviews (Agustian, 2019). The affective dimension of students' understanding also necessitates verbalisation and elaborate description, rather than prescribed options typically administered through closed-ended questionnaires (Galloway et al., 2016). The interviews from the larger research project on students' learning were divided in two. The first half pertained primarily to students' learning experience and goals in the laboratory, with some exploratory queries on their views of science, particularly their understanding of the origin and justification of scientific knowledge. The second half was mainly on evaluating their views of the nature of science. Following up the VNoS questionnaires, students were interviewed on their views of NoS aspects in the context of laboratory. The semi-structured interviews consisted of several questions on elaboration of the statements in VNoS Form B, as well as additional questions derived from VNoS Form C. For example, the following statement from Form C was used to evaluate students' views on theory-ladenness and philosophical subjectivity in science:

> It is believed that about 65 million years ago the dinosaurs became extinct. Of the hypotheses formulated by scientists to explain the extinction, two enjoy wide support. The first, formulated by one group of scientists, suggests that a huge meteorite hit the earth 65 million years ago and led to a series of events that caused the extinction. The second hypothesis, formulated by another group of scientists, suggests that massive and violent volcanic eruptions were responsible for the extinction. How are these different conclusions possible of scientists in both groups have access to and use the same set of data to derive their conclusions?

Table 1. *Simplified Criteria for Evaluating Students' Level of NoS Understanding*

NoS Aspects	**Level of Understanding**		
	Naïve	**Transitional**	**Informed**
Empirical and inferential nature of science	Focuses responses on only empirical evidence and has a particular focus on being able to see all aspects of what is being studied (even if it cannot be seen)	Understands that the atom is a model and that you cannot see it, but they are still overly focused on empirical data	Knows that inferences have to be made to create models, particularly about things that cannot be seen; knows that models are used to make additional inferences
Tentative nature of scientific knowledge	States that scientific theories do not change or thinks that scientific theories change because they are guesses or opinions	Acknowledges that scientific theories change, but the explanation is general or vague or there is no explanation	Understands that theories change and provides a reason and explanation as to why these changes occur
Scientific theories and laws	Subscribes to a positivist and static view of laws and theory and a hierarchical view between them	Has a tentative view of at least one of them but inadequate elaboration of their roles	Adequate understanding of the difference of their roles in science
Creativity and imagination in science	Says that scientists cannot be creative or cannot use imagination or says that they can use it only to fix bad experimental designs	Says that scientists use creativity and imagination but without elaboration	Creativity and imagination are needed throughout scientific process
Philosophical subjectivity and theory-ladenness	Indicates that coming to different conclusions from the same set of data would be because the data are bad or says that two scientists would not come to a different conclusion about the same data	Says that scientists can look at the same set of evidence and come up with different interpretations, but their explanation is overly simplistic or based on a perceived opinion of the scientist	Indicates that scientists can look at the same set of evidence and come up with different interpretations and provides a good explanation as to why
Social and cultural embeddedness	Believes that science is universal and devoid of any social and cultural influences	Mixed of universalist and contextualised view of science	Understands that science is contextualised in a larger social and cultural milieu

Data Collection and Analysis

Prior to data collection, ethical approval was secured through School's Research Committee, according to the British Education Research Association guidelines (BERA, 2011). Students were well informed about their voluntary participation in the study, their right to withdraw at any time during the investigation, as well as anonymity and data confidentiality. Throughout the project, 129 students participated in questionnaires data collection, 30 of which responded to the VNoS Form B questionnaires. A total of 14 students participated in the interviews, six of which were evaluated with regards to their views of NoS. The interviews were recorded, upon their informed consent. Verbatim transcriptions were then analysed using NVivo, to discern emerging themes and map students' NoS understanding into three levels.

Students' views of NoS were evaluated in accordance with criteria for the level of NoS understanding (see Table 1). These criteria are a simplified version of a more sophisticated judgement (informed by the critical review of literature to warrant validity) and nuanced assessment of their responses. During the data analysis and interpretation, students' responses were weighed carefully, compared to other aspects (principle of interdependency of NoS), and coded accordingly, in order to warrant reliability.

Results

This section is divided into two parts. The first one results from the qualitative part of data collection and analysis done in the first half of the project. The aim of this phase is to explore students' views of the nature of science, especially the tentative nature of scientific knowledge, and get a general impression of their level of understanding. A possible association with pre-laboratory activities is also explored. The data from this exploratory phase informs the design of the following phase, which is more evaluative.

Eight third-year students agreed to participate in the semi-structured interviews of the exploratory phase, where four of them were males and four were females. One was a student whose English was not a first language. Six third-year students agreed to be interviewed in the evaluative phase, where one was female and five were males. All six were international students and English was not their first language. In the rest of this article, references to each of these interviewees will be labelled with superscripts 1 to 8 (exploratory phase) and 9 to 14 (evaluative phase). The interview protocol of the first phase consisted of three big sections on pre-laboratory, the nature of science, and information management, whereas the second phase consisted of sections of the new two-part laboratory structure and the nature of science. Each question aimed to elicit their experience in the laboratory from cognitive, epistemic, psychomotor, and affective viewpoints. Each interview took approximately 40 to 60 minutes. NVivo coding was used to identify salient features and emerging themes.

Phase 1: Exploration

One of the research questions being investigated in this project is to what extent the pre-laboratory work informs students about the nature of science. Students were asked about their views on a statement about one of NoS aspects, as follows:

> Some scientists believe that explanations of chemical phenomena, such as atomic theory, are accurate and true descriptions of atomic structure. Other scientists say that we cannot know whether or not these theories are accurate and true, but that scientists can only use such theories as working models to explain what is observed.

The interviews also probed into their experience with regards to science in general and the extent to which instructional features in pre-laboratory informs them about NoS.

Students' Perceptions on Nature of Science

Students agreed that theories are working models to explain what is observed[2,3,5,6]. They all believed that pursuit for knowledge in science is an ongoing process. One student maintained, "I'm leaning more towards the second one. I find it difficult to be able to … believe that you can know something definitively,"[6] whereas another one argues,

> I think it's true how a lot of it is just a model that helps explain what's going on, because for example, molecular orbital theory, is a big theory that explains a lot of stuff but it's more a mathematical approach to explaining something, as far as I understand.[2]

Students acknowledged that knowledge is not static[1,2,5,7,8], and 'that is the interesting thing about science, how it's always changing'[2]. A student held the view that '[w]e can only use the knowledge we've got, then … we build up our repertoire using that knowledge'[3]. 'People thought the atom [was represented by] the plump pudding model, a mass of positive charge and negatively charged electrons. … [We know now that] it expands and it completely changed, just like the whole atomic structure. It's been developed over the past centuries'[2]. As such, knowledge is tentative and 'will keep developing'[1].

The discussion on this topic also gave a hint of how students did not subscribe to scientism[1,2,4,6], as one asserted, '[t]here's so much we don't understand in the world … to say something is absolutely the way it is'[6]. Science aims to explain how nature works, as one put it rather boldly, 'the point of science is to find truth [about nature]'[2], but another concedes, 'I don't think we don't know the whole truth'[4].

Scientific methods are among the aspects of Nature of Science and students acknowledged the importance of applying these[2,4,5,7]. One intimated, 'those scientist that don't believe it's true, I can understand their viewpoint, because they want to see evidence … and science is collecting evidence'[5]. In a sense, 'science is a bit philosophical'[2], in which one cannot just have faith[5]. Science 'is not magic'[4] or religion for that matter.

Instructional Features That Might Influence Views of NoS

In general, students did not think that the current pre-laboratory provides them much insight into Nature of Science or if they get understanding of NoS from pre-lab[2,3,4,5,6], which was not surprising, as NoS was not made explicit in any of the pre-laboratory activities or resources. One conceded that he 'never had any thought beyond the experiment'[3], whereas another one said that '[t]he idea of science … [was] not something that [she] really spen[t] much time thinking about'[6] during the learning continuum of laboratory. One student explained why this was the case,

> 'You can never know everything. So sometimes when I read the manual, I can get slightly caught up in those details rather than focussing on just accomplishing what I need to accomplish.'[5]

Notwithstanding the initial lack of reference to NoS in pre-laboratory, a student maintained that pre-laboratory videos gave a hint of how science works[4]. Another student asserted, '[i]n terms of how science works, partly, [the pre-laboratory videos] definitely addressed the best experimental procedure, … [they] often speak of reliability [and] accuracy of results'[3]. Students tend to think that the pre-laboratory videos focus more on experimental aspects[2,4]. The part on theory is usually not in-depth, but it encourages them to think about 'why [they] are doing it'[1].

Interestingly, students believed that report-writing provided them with opportunities for thinking more about science and the chemistry behind the experiment they have done. One described,

> 'I think report writing is interesting because in phys[ical] chem[istry], … you have to do your own reading. It's not like in organic chemistry experiment where you [are given a prescriptive instruction of] … what happened. [In this laboratory] you have to look into it, understand it, … It gives you thinking about what's happening, what you're doing makes sense.'[2]

Time constraints during the experiment in the laboratory is believed to be much less of a problem during the write up process, as one student maintained, 'there's a lot of independent study that we had to do quite long [during the report writing] and you have to understand what's going on. So that's a good place to start investigating. You have to find out sources and not always stuff you've been told in lectures … to be able to back up what you've found'[1].

Wider Context of Laboratory Education

An interesting, salient theme emerged from the discussion on Nature of Science, as students reflected on their experience as a student of an undergraduate chemistry programme at this university. One compared different modules, whereas the other different years.

> 'I've done a range of modules, tried everything out, and the only module I really enjoyed … learning … was environmental chemistry, cause it was applicable. I could see how it was useful in society. … It was explained how gases are in the environment, the toxicity of metals in the body. Once we learn difficult theory, it was relevant a thing, you could see it in the world around you. You could discuss it with people.'[3]

Relevance and real life application are recurring themes in the other parts of interviews[2,3,6], and social context of science is an aspect of NoS that could be made more explicit in pre-laboratory. It is a facet of chemistry that instils 'enthusiasm and interest'[3], which is one of the main reasons why the students chose to do a degree in the chemistry in the first place.

Phase 2: Evaluation

In the second phase of the research project, an adjusted version of Views of Nature of Science, Form B (Lederman et al., 2002) was administered to third-year students in the physical chemistry laboratory. The new two-part laboratory structure was taken into consideration in both data collection for this questionnaire and the student interviews. This new structure was argued and exemplified elsewhere (Seery et al., 2018a; Seery et al., 2018b). Informal conversations with students and demonstrators were conducted during an unstructured observation. Students were to complete the questionnaire whenever they had time in between their laboratory activities. Due to the open-ended nature of the questionnaire, a number of students were not able to finish it.

The evaluation was meant as a glimpse into the students' views of NoS at some point in their laboratory experience, rather than an assessment of any changes in their understanding. The rationale for this is, just like in the previous phase of the study, there was no intervention involved in this research. The new two-part structure of the laboratory was designed not in the context of this research project, but rather the other way around, so the data collection followed this alteration in the way the laboratory instruction was designed and organised.

Questionnaire Data

Thirty students returned the VNoS-B questionnaires. Considering the open-ended nature of the instrument and the time frame in which they were administered, this was expected. It was also expected that most students would give a rather concise response to the seven statements. However, several participants went to great lengths to elaborate their views. Their written responses were analysed using the aforementioned criteria and mapped into a chart, as shown in Figure 2. An excerpt of data analysis is shown in Table 2.

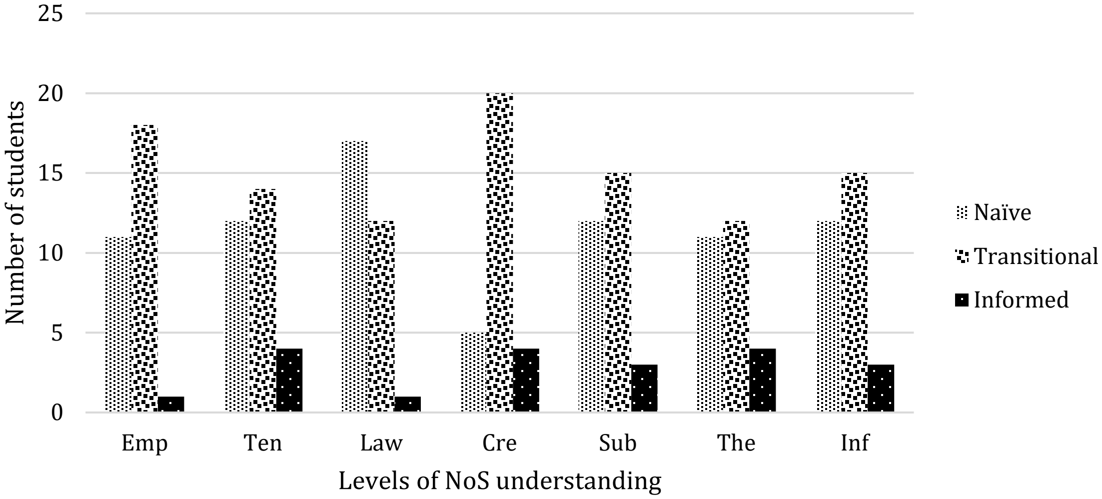

Figure 2. Students' levels of NoS understanding mapped from VNoS questionnaires. *NoS Aspects:* Emp = Experimentation and empirical nature of science; Ten = Tentative nature of scientific knowledge; Law = Scientific theories and laws; Cre = Creativity and imagination in science; Sub = Philosophical subjectivity; The = Theory-ladenness; Inf = Observation and inference in science

Interview Data

Akin to the previous cycles of data collection, students' interview responses were transcribed verbatim. The interview transcript from the evaluative phase amounted to approximately 14,000 words. To get a general impression of what was mostly referred to during the interviews, word frequency query was run on responses from interviewees' 9 to 14 (*Figure 3*). Each quote was labelled to refer to the interviewee. For instance, Interview 3.13 means that it belongs to student 13. The numerical references associated with interview quotes are consistent throughout this manuscript. Each code extracted from the data was further mapped into three levels of NoS understanding, *i.e.* naïve, transitional, and informed views, referring to previous studies on NoS assessments, as shown in Figure 4. The following subsections are the findings from this evaluation.

Table 2. *Excerpt of Questionnaire Data Analysis, whereby Levels of NoS Understanding are Represented by white (naïve), light grey (transitional), and dark grey (informed)*

ID	Tentativeness of Knowledge	Inferential Nature of Science	Scientific Theories & Laws	Empirical Nature of Science	Creativity & Imagination in Science	Subjectivity in Science	Theory-ladenness
1	Yes it is tested in many ways to see if the theory holds up and that there are no exceptions. If exceptions arise, the theory is revised to accommodate these exceptions – and repeat.	I'm sure some scientists are sure by the use of quantum mechanics although I feel as quantum mechanics is a difficult field to draw conclusions of, the structure of the atom is nowhere near as defined as it could, and will be.	Theory is for building laws upon – the theory cannot really be proven wrong or right without an accompanying law. V=ik is a classic law that holds up to scrutiny, whereas the theory of relativity was controversial and unsure until proof was given, backing up that theory.	Similarities can be drawn. Maths, as the science of number can be linked to all of music, a form of art, and how we interpret musical rhythm, harmony and melody. Music is just varying rations of vibrational waves which our ears understand very accurately in rations such as 2:1 (octave), 3:2 (fifth) if the freq is 20-20,000 Hz.	I guess they use some creativity and imagination as some scientists find very useful new techniques to analyse data although a lot of it is just following tried and true techniques of data analysis – not saying this is much different to art as that happens very often, there two-linking the two subjects again.	Science is based on facts, but I feel science is a growing subject where facts are in place as scaffolding therefore it should be encouraged to test the boundaries of what known are facts, therefore people should have an opinion on what scientific knowledge is just scaffolding for a bigger idea.	NA
4	Yes.	As certain as they can be given current limitations of tech and theory. Never 100% certain as you don't know how far things will advance in future.	Yes – laws are set and can't be disproved, theories are never completely set otherwise they would become laws. Theories are based on laws.	They are both creative for people at the top of their profession. In general science is more fact based whereas art is often more subjective. Science can be used in the explanation of art but art is not used in the explication of science.	Not so much during as you should just be following the experiment/investigation you've designed. Fore sure after data collection.	Scientific knowledge is a widely regarded opinion. Not all opinions are scientific fact and knowledge lies somewhere in between.	Different theories, based off different knowledge, based of different opinions.
5	Yes a theory can always develop to a greater extent with the passage of time.	They are certain about the components found in an atom but not how they are arranged.	Yes the difference is that theories are often based on laws.	Both science and art have progressed when original ideas are introduced in the respective field.	Yes when analysing data and observing new trends.	Scientific knowledge is a highly accepted scientific opinion.	Data can be interpreted in different ways if conclusion made are based on different theories.
8	Yes, it can change if evidence is provided to either disprove and therefore change or further prove science is always changing.	Pretty certain as there is strong experimental evidence to support it. However there is no saying whether more evidence will come along and change it.	A scientific law shows what is happening in the form of a formula such as E=mc2. A scientific theory explains what is happening. An example of this is molecular orbital theory.	Science and art are similar in the way they are creative and they aim to understand the world we live in. They are different in the methods they use and in the people they attract.	Interpreting data and presenting it within a lab report can be seen as using creativity and imagination.	Yes, as a person can have scientific knowledge and no scientific opinion and vice versa.	The way a scientist interprets data can be completely different to the way another scientist does, therefore reaching different conclusions.

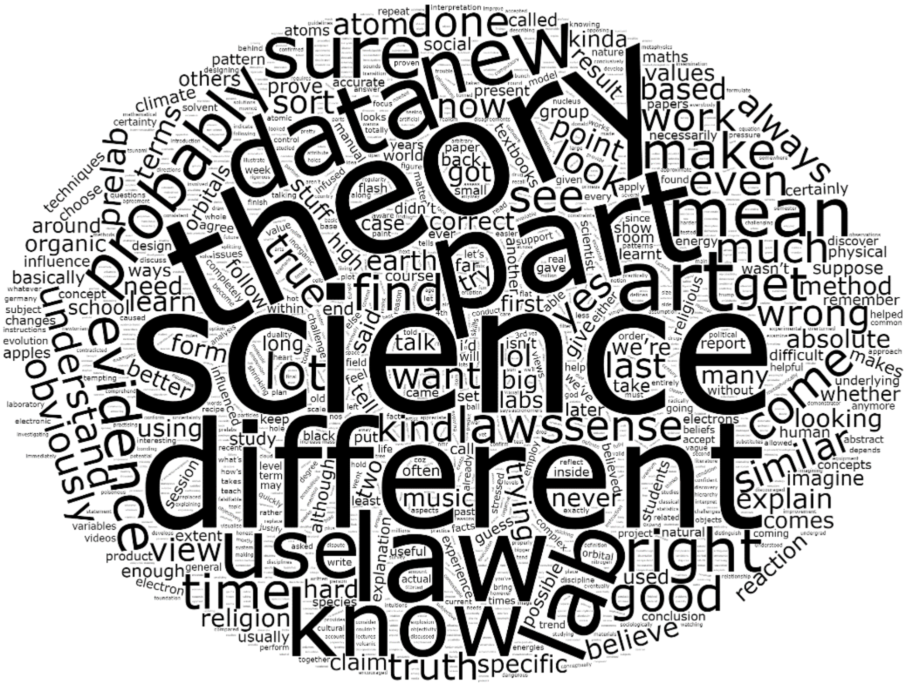

Figure 3. Word frequency query on the NoS interview data.

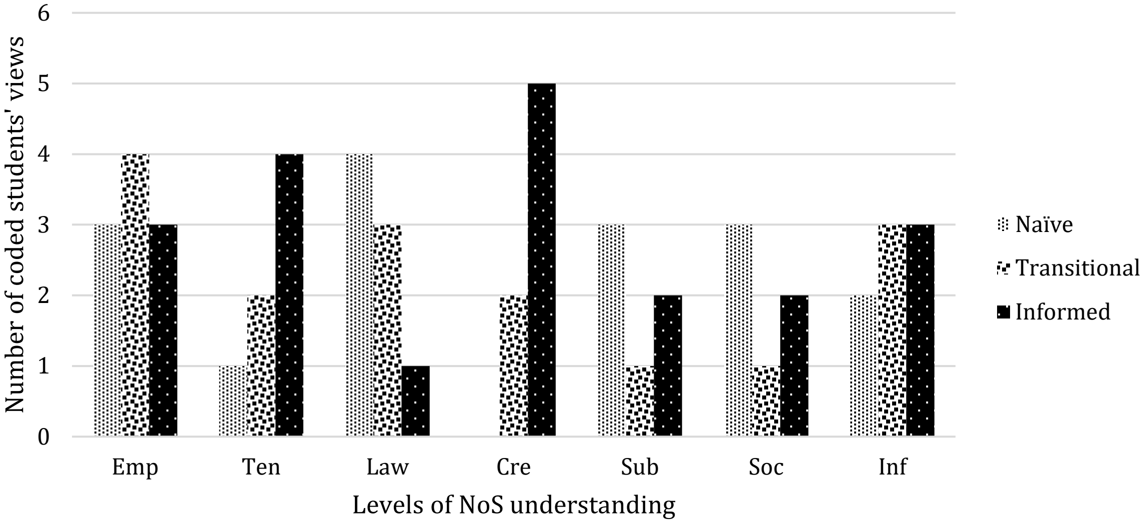

Figure 4. Students' level of NoS understanding mapped from the interviews. *NoS Aspects:* Emp = Experimentation and empirical nature of science; Ten = Tentative nature of scientific knowledge; Law = Scientific theories and laws; Cre = Creativity and imagination in science; Sub = Philosophical subjectivity and theory-ladenness; Soc = Social and cultural embeddedness; Inf = Observation and inference in science

Experimentation and Empirical Nature of Science

Several responses coded from three students'[11,12,13] views on experimentation and empirical NoS are considered naïve. Other responses from four students[9,11,12,13] fall into transitional category, and three others[10,12,14] are considered informed views of this aspect.

Table 3. *Excerpt of Data Analysis: Experimentation & Empirical Nature of Science*

Quotes and codes (in bold)	Analysis	Level
Interview 3.13 Reference 1: 1.10% coverage I think theory from science is **always proven by experiments** or something happens from nature. We have to show with our data or result, we have to **prove it**.	Experiments are not conducted to prove theories but support them.	N
Interview 3.11 Reference 3: 1.56% coverage Obviously they are quite different, because … **science is very strict** and you try to find **the truth** and art is about your own truth and what you want to communicate and the reaction you want people to have looking at your art, and there's **not much freedom in science**. There's only like **one answer** we have to find out. It's not like what you think or what you like that answer to be like.	A reference to 'the one and only truth' in science is naïve. A view of science as a strict, rigid entity is ill-informed and misled.	N
Interview 3.12 Reference 1: 1.11% coverage Science is **based on evidence** and it **can be tested over and over**. And the same result comes out. It's a **direct reflection of materials**, states. It **can't be rationally argued against**, because of the evidence. So that's the main difference between physics and metaphysics.	Proper reference to the empirical base of science but still a rather naïve understanding of the infallibility of science.	T
Interview 3.10 Reference 1: 1.77% coverage So, if you have an understanding of … for example some mechanism that's accepted, … and then you have this new reaction that doesn't conform to the mechanism, … you can **use this understanding from the old theory** to understand why that reaction doesn't conform, or maybe you can **propose an explanation into why it doesn't work and make a new theory**, or new mechanism.	Adequate argument, example, and elaboration.	I
Interview 3.14 Reference 1: 4.05% coverage We were talking about … field of knowledge, **ways of knowing**. There are different ways of knowing, and religion is one of them. It's a matter of how we **approach and justify knowledge**. How we **form our thoughts and conclude** that specific field. [A proper example is given] Because in **science you have someone else**, … you can **reproduce it in a way that you can verify** what others have done. In religion you can't necessarily produce the same result.	Adequate argument and elaboration.	I

Tentative Nature of Scientific Knowledge

Several responses coded from one student's[11] views on tentative nature of science are considered naïve. Other responses from two students[9,10] fall into transitional category, and four others[9,10,13,14] are considered informed views of this aspect.

Table 4. *Excerpt of Data Analysis: Tentative Nature of Scientific Knowledge*

Quotes and codes (in bold)	Analysis	Level
Interview 3.11 Reference 1: 1.44% coverage [T]here are **paradigm shifts**. Obviously it's **not so common**, because they do experiments and they think **what they found is the truth**. And then maybe there's something that they didn't look at, like it happened with physics for example, and **everything changes**. But I would say most of the knowledge we have is probably quite **accurate**.	Although there is a reference to paradigm shift, the explanation was incorrect. There are still mentions of "the truth." Also, together with the rest of responses and examples given, the NoS view is considered naïve.	N
Interview 3.9 Reference 1: 0.12% coverage [Theories] **changed until it's empirically correct**. Reference 2: 0.32% coverage It's difficult to talk about the capital T, Truth, when you have some sort of **incommensurability** between the theories	Proper reference to Kuhn's principle of incommensurability and tentative nature of scientific theories, but there is also a reference to "the capital T, Truth."	T
Interview 3.10 Reference 1: 2.17% coverage [M]ost **theories eventually [changed]** as the understanding progresses…, they might just **become a new theory**, might just **evolve**. The new theory might be **used together** with the old one. For example, we still use [valence bond theory] although we know there's some inherent mistake in it.	Adequate explanation of the development (and replacement) of theories and the use of them in a current context.	I
Interview 3.13 Reference 1: 2.04% coverage I think **theories always change** ... People used to think that Earth was flat, but now we know that it's round. Since there's a lack of knowledge, even though science is much developed now, we still have to look forward. … I think some people believe this one, but later on when there's a new discovery, this one is **taken over by new theories**.	Adequate explanation of the development (and replacement) of theories.	I
Interview 3.9 Reference 2: 0.19% coverage In physics we went from **Newtonian mechanics to Einsteinian mechanics**. Reference 6: 2.06% coverage [Q]uantum mechanics is **not our final theory**. There's still undeveloped issues and most of the things that chemists work with is **approximation** anyway. [Q]uantum mechanics **isn't entirely consistent** with relativity theory either. So one of them must be at least developing. **I don't think we're at the end**.	Adequate explanation of tentativeness of knowledge and approximation in science. The rest of the response (edited out here) also supports his view. Proper example and elaboration.	I

Scientific Theories and Laws

Several responses coded from four students'[10,12,13,14] views on scientific theories and laws are considered naïve. Other responses from three students[10,11,14] fall into transitional category, and one other[9] are considered informed views of this aspect.

Table 5. *Excerpt of Data Analysis: Scientific Theories and Laws*

Quotes and codes (in bold)	Analysis	Level
Interview 3.10 Reference 4: 1.33% coverage I think there's a difference in that you don't really have to understand the theory as long as you know the law. So in that terms I think a **law might be higher**. For example there's more theories to explain the law. The **most important thing is the actual law, not the theory**, although the theory might help you understand more or expand.	A clear hierarchical view of scientific theories and law is considered naïve.	N
Interview 3.13 Reference 1: 0.85% coverage As far as I know, I think **law is never changing**. So scientists can come up with a theory but this can be contradicted by another theory. But I think **laws are like firm and set**. Reference 2: 0.62% coverage [For example] thermodynamics law. It **never changes**; it's **permanent**. I can come up with any theory and other people can say that's wrong.	Akin to theories, scientific laws are also subject to revision and change. Theories and laws just serve a different function in science.	N
Interview 3.14 Reference 1: 1.44% coverage Scientific theory… it has been confirmed that it's working. At the same time, it's called theory because it doesn't explain everything. Just like molecular orbital theory. Theories are **guidelines**, in a sense. They **predict** that things usually go this way, but they're **not fully perfect**.	There's a merit to this elaboration, but his view on scientific law is still naïve.	T
Interview 3.9 Reference 1: 0.58% coverage [L]aw is… sort of ill-defined… and somewhat misleading term, because we always have the **association from legal** things that laws govern. But maybe that's **not exactly what we mean by laws in science**. Reference 3: 0.85% coverage I would take some sort of **Humian perspective** in a sense that law is **regularity** as opposed to, I suppose, **dispositionalism**, things are and do act in a certain way. I think it's difficult to really be satisfied with either explanation. Reference 4: 1.33% coverage [Theory] is definitely not the same [as it] **describes** more of an **overall framework**, whereas laws might be something that **underlies the theory**. … So just how we employ the term rather than… we talk about N-O theory rather than molecular laws. Laws are underlying things we employ to something like thermodynamics.	A rather sophisticated elaboration on what scientific law is, making a reference to philosophy of science.	I

Creativity and Imagination in Science

There is no naïve view on this aspect. Several responses coded from two students[12,13] are considered transitional. Other responses from five students[9,10,11,13,14] are informed views.

Table 6. *Excerpt of Data Analysis: Creativity and Imagination in Science*

Quotes and codes (in bold)	Analysis	Level
Interview 3.12 Reference 1: 2.15% coverage You use your imagination **to come up with the solutions**. I think if you have **to come up with new theories**, using your imagination…. I think all these great scientists like Einstein or Stephen Hawking, they were supposed to be good at using creativity and imagination. H: What about practising scientists in general? 12: I don't think so. I don't know. Maybe I'm wrong. I'd like to be wrong, but I really don't think so.	True, but the explanation falls short. Not only prominent, high-profile scientists use creativity and imagination. Students doing science, are in fact, also creative and imaginative to different extents.	T
Interview 3.10 Reference 1: 1.29% coverage They probably have to be creative in order **to explain data**, for example the data was not expected, which very often happens for various reasons. Reference 2: 0.85% coverage **During the data collection**, I think they still have to be creative, for example in order to figure out ways how to arrange an experiment so that there's no air in the reaction vessel. Reference 4: 1.07% coverage If you're studying black holes and you don't know what happens when something enters the black hole. I'm sure there's a lot of imagination in **thinking what might happen**, when it's so far away and it's practically impossible to see what's happening.	Adequate argumentation and examples.	I
Interview 3.9 Reference 5: 0.68% coverage Creativity is probably the more narrow concept, but even that… I would certainly say yes they do use, because even once you have your data, you still have to **know what it tells you**, what kind of **analysis you have to do**. That's the creative aspect of science. Reference 6: 0.97% coverage Imagination seems like the more fundamental concept. Imagining **underlines all thought about something that's potential**. [W]henever you plan to take something in a certain direction, or you have to do certain things with the data, or whatever, you use your imagination.	Adequate argumentation and examples.	I

Philosophical Subjectivity and Theory-ladenness

Several responses coded from three students'[11,12,14] views on this NoS aspect are considered naïve. Other responses from one students[9] fall into transitional category, and two other[9,10] are considered informed views of this aspect.

Table 7. *Excerpt of Data Analysis: Philosophical Subjectivity and Theory-ladenness*

Quotes and codes (in bold)	Analysis	Level
<u>Interview 3.10</u> Reference 4: 1.33% coverage I think there's a difference in that you don't really have to understand the theory as long as you know the law. So in that terms I think a **law might be higher**. For example there's more theories to explain the law. The **most important thing is the actual law, not the theory**, although the theory might help you understand more or expand.	A clear hierarchical view of scientific theories and law is considered naïve.	N
<u>Interview 3.9</u> Reference 1: 1.23% coverage [Art] **doesn't make a claim quite exactly or unfalsifiable** in the way that science usually does. So in that way it would be odd to ask an artist to say, oh… how's your painting falsifiable? How can I say that this is objectively true? Reference 2: 0.83% coverage [O]nce you … conclusively show something, you **can't dispute it anymore**. So once you conduct experiments that no one can reasonably object to, you can't claim both things anymore.	Akin to theories, scientific laws are also subject to revision and change. Theories and laws just serve a different function in science.	T
<u>Interview 3.9</u> Reference 1: 1.15% coverage Another challenge is the **values that underlie your theory** choice. So what kind of theory do we employ … has to be linked to subjectivity. Because we want our theory to **be internally and externally consistent**. We want them to be as simple as possible. Those are the things that you can link to this objectivity. But that's also being challenged in that some people say maybe we should **be ontologically diverse**.	Very thoughtful and balanced argument, drawing some reference to the philosophy of science. This is a sophisticated view of philosophical subjectivity and theory-ladenness.	I
<u>Interview 3.10</u> Reference 1: 0.97% coverage I mean it's possible that the **data can be explained by two theories**. I'm not sure which one would be the more true one, but they might both be **equally valid**, given the data, whereas some geological features might be explained by both theories. Reference 2: 2.00% coverage I'm sure there's **uncertainty** in dating of the data where it might be unsure when the last dinosaur actually lived, where the data is limited, given the fossils. And I'm sure … **not all researchers working on that have all the data available**. They might be just focusing on some.	Proper reference to philosophical subjectivity and adequate argumentation and examples.	I

Social and Cultural Embeddedness

Several responses coded from three students'[11,12,13] views on this NoS aspect are considered naïve. Other responses from one students[10] fall into transitional category, and two other[9,14] are considered informed views of this aspect.

Table 8. *Excerpt of Data Analysis: Social and Cultural Embeddedness*

Quotes and codes (in bold)	Analysis	Level
Interview 3.11 Reference 1: 1.45% coverage I would say it's **universal**, because it's **based on evidence**, not just some thoughts and opinions. So when you talk about evidence, evidence is just **the same regardless of your cultural upbringing or religion** or whatever, and that's why scientists from all over the world can collaborate to work on the same thing. Because it's not a social science, it is universal.	A universalist view of science is considered naïve.	N
Interview 3.12 Reference 1: 1.01% coverage I think it should be **universal**. Religion is more infused with social and cultural values. I think science deviates from that. It can be more trusted in telling **the truth**, because the truth is sometimes different from social and cultural values.	A universalist and absolutist view of science is considered naïve.	N
Interview 3.10 Reference 4: 2.02% coverage That could definitely reflect that science in a heavily religious country might be different from an atheist country. Or when research is taboo from some other reasons. For example, the research on … artificial insemination might be discouraged in religious countries. I'm sure there are more examples. But it depends on the subject where some are more universal, some are **more influenced by social factors**.	Regardless of where it is conducted, science is always influenced by social and cultural values.	T
Interview 3.14 Reference 1: 3.10% coverage Historically, we know that there were people who tried to twist science. For example, in 1930s someone claimed that one race was better than the other races, justified by the size of the skulls. Or, some data from 1970s that cannabis is a gateway to drugs. Let's make a war on drugs. Yes, we have uniform, universal facts, but it's how we shape them that matters.	Adequate view and proper examples.	I

Models and Inference in Science

Several responses coded from two students'[9,14] views on this NoS aspect are considered naïve. Other responses from three students[10,13,14] fall into transitional category, and three other[10,11,12] are considered informed views of models and inference in science.

Table 9. *Excerpt of Data Analysis: Models and Inference in Science*

Quotes and codes (in bold)	Analysis	Level
Interview 3.14 Reference 1: 1.10% coverage We are **certain** about 60-70%, at the same time, we have Heisenberg certainty saying that we'll never know where an electron is. We can think of electrons as a cloud. The visualisation of orbitals is captured in one specific time, in this context.	Naïve reference to visualisation as a real structure of atom.	N
Interview 3.13 Reference 1: 1.72% coverage I don't think we are very sure about it, because atom is literally very small. We can only come up with **hypothesis or theories**. Since it's very small and they're like unknown world, I don't think scientists are very sure. They are trying to discover more about it, but I think there should be more to atomic theory. We still have more to discover.	Proper reference to uncertainty but inadequate explanation.	T
Interview 3.12 Reference 1: 3.83% coverage We are at a certain level of certainty [about the structure of atoms], but that scale could be to an infinity. I don't think [we will ever have 100% certainty]. Because from a philosophical point of view, … we could be more accurate in our description of what the things look like but I don't think we'll ever get an objective feel of what it really is. So, the **representation of an atom** is a way of looking at an atom and the image that I have of you is a way that I can look at you. But in both ways, there's a lot of inaccuracies there. I don't think I can ever get 100% accurate view of anything. Even like a bottle or anything.	Adequate description of inference about the structure of atom and the level of certainty about it.	I
Interview 3.11 Reference 1: 2.16% coverage I think we have a good knowledge today, but I also think that it's so **abstract and complicated** that you can't just teach it to high school kids. You have to sort of give them an **easier thing to represent** it. But obviously you can go into physics and study it from a different perspective and it's just not a little ball with a nucleus and electrons spinning around it. I think it's just a way to… coz like human finds it easier to **visualise** things. So even for me, for example, it's easier to think about it that way than some abstract quantum mechanics.	Proper explanation of the function of inference and balanced view of the certainty level.	I

All interviews were mapped into levels of NoS understanding, as shown in Figure 4. In comparison to the questionnaire data, there is a slight difference in the NoS aspects being addressed.

VNoS Form B addresses theory-ladenness and subjectivity in science in two separate questions, but there is no specific statement on social and cultural embeddedness of science. In this study, the interviews addressed the former two aspects under one, that is, philosophical subjectivity and theory-ladenness, and the social and cultural embeddedness were also discussed.

Discussion

I set out to explore and evaluate undergraduate students' views of the nature of science in the context of the chemistry laboratory. In order to locate the study in an appropriate theoretical framework, arguments for laboratory education in undergraduate chemistry and the inclusion of the nature of science instruction in laboratory context were made. I was particularly interested in the pedagogical and philosophical validation of undergraduate laboratory curricula, which has been scarcely researched in the literature.

Initial finding revealed that in terms of students' understanding of the tentative nature of science, they seemed to subscribe to a dynamic view of scientific knowledge (Songer & Linn, 1991). In this view, ideas in science are regarded as changing and developing entities and the best way to learn about them is to understand what they mean and how they relate to one another. Bell and Linn (2000) describe how this static *viz a viz* dynamic views of science influence students' learning strategies. Those who subscribe to the former tend to think that the best approach to learning science is by memorising facts and concepts (see also, Tsai, 1999), whereas those who subscribe to the latter tend to prefer understanding as the best approach.

The aforementioned finding is different from that of Yacoubian and BouJaoude (2010), who investigated 38 high school students doing an inquiry-based laboratory course. Their initial evaluation of the students' NoS views, prior to an intervention, resulted in predominantly naïve views. Only after an explicit, reflective pedagogical intervention did most of those students change their views of NoS. The difference in the average level of students' understanding of NoS between the present study and that of Yacoubian and BaouJaoude prior to their intervention could be attributable to the higher level of scientific literacy of our chemistry majors. Inarguably, this necessitates further substantiation. I argue that a pedagogically and philosophically valid NoS instruction could elevate the students' level of understanding.

The exploratory investigation into students' views of the tentative nature of scientific knowledge was substantiated further through the evaluative phase, using both versions of Views of Nature of Science (Form B and Form C). This phase also assessed other aspects of NoS, including the social and cultural embeddedness of science. Questionnaire results indicate that most students were on a transitional level of NoS understanding, for all aspects except scientific theories and laws, where they had naïve views. This was also indicated in the interviews.

Naïve understanding of the difference between scientific theories and laws, their distinctive roles in science, and the non-hierarchical relationship between them, proved to be rather common among students. Similar to this result, Liang et al. (2006) found that the majority of students from the US, China, and Turkey believe that scientific laws are proven theories. The authors argue that informed views about this NoS aspect acknowledge that scientific theories and laws are merely two different types of knowledge, neither of which are certain.

Notwithstanding the predominantly transitional views among undergraduate chemistry students in this study, further investigation shows that there were more informed views captured by the interviews. With regards to creativity and imagination in science, there were roughly more than twice informed views than that of transitional views. None of the six students had naïve views of this aspect. A student posited, 'When you change a variable in an experiment and see how other variables are changing, you have to be creative enough to explain why it happens. Imagination is even more. You need to think of new breakthrough ways to see if a theory is wrong'[14]. Duschl and Grandy (2013) agree that understanding data is a complex and lengthy process. It requires considerable amount of ingenuity and creativity on the part of the scientists. Although scientists are sceptic of both data and its interpretations, they can also resort to imagination and speculation to develop theories that might represent aspects of nature (Taber, 2017). Echoing this, Bell et al. (2016) assert that creativity permeates all aspects of scientific investigations, from hypothesis generation to data interpretation.

The data also reveal that the profile of students' views of subjectivity and theory-ladenness in science mirror that of NoS in the context of laboratory as a whole. The naïve views in relation to the transitional and informed views are roughly in proportion of 4:5:1. As previously stated, students' views of the nature of science in the context of laboratory are predominantly transitional. Bell et al. (2016) argue that scientific knowledge is influenced by theory that acts as a lens through which questions are developed, investigations are designed, decisions concerning data collection are made, and results are interpreted. When a new hypothesis is proposed, researchers try to assess its credibility by discussing the new theory in light of accessible empirical evidence and the massive network of existing established knowledge (Lunde et al., 2016). These phenomena account for subjectivity in science. However, Matthews (2012) concedes that this conception can be ambiguous. Acknowledging that science is theory-laden is not equivalent to saying it is subjective in the everyday psychological meaning of the term. Matthews' critique on Lederman's research group's definition of this NoS aspect was resolved with what he coins as 'philosophical subjectivity', which is also adopted in this study. He argues further that the entire history of modern science is an effort to minimise the psychological subjectivity in measurement and explanation. A student maintains, 'the values that underlie [our] theory choice… [are] linked to subjectivity, … [because] we want our theory to be internally and externally consistent'[9].

Conclusion

This study was conducted on a rationale that laboratory education, particularly at university level, seemed to escape the knowledge development in the nature of science. Thirty-six third-year undergraduate students doing a course in inquiry-based physical chemistry laboratory were evaluated, using Views of Nature of Science assessment instrument and assessment criteria that characterise their views into three levels of understanding. The findings reveal that, in general, the participating students had transitional views of the nature of science. Compared to a previous study on NoS evaluation of high school students in the context of science laboratory (Yacoubian & BouJaoude, 2010), students in this study fared slightly better. Based on the findings, I argue for incorporating the nature of science in undergraduate laboratory education. However, further substantiation involving an evidence-based pedagogical intervention is needed in order to establish the extent to which such intervention is effective.

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