Learning in the tertiary level chemistry laboratory: What we have learnt from phenomenology research

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In 1915 E. B. Spear posed one of chemistry education's persisting questions: Is the potential of chemistry laboratory instruction being effectively realized? Despite its widely professed centrality, the academic chemistry laboratory is often a neglected area of teaching and, it could be argued, of research as well. Research has mostly focused on secondary education, single institutions, and isolated interventions assessed quantitatively using performance on cognitive outcomes as opposed to searching understanding of broader aspects of learning through experimentation. This chapter argues for the need of tertiary-level, subject specific research that shifts from a fragmented and instruction-based emphasis to one that is comprehensive and learning-centred. It introduces some of the foundational ideas and building blocks that support a dedicated research programme in this area. Furthermore, this chapter puts forth qualitative approaches such as phenomenology may be better suited to deal with the complexities of learning through experimentation. To conclude, it briefly discusses exemplar phenomenological studies that have investigated learning experiences of students and their instructors in the college chemistry laboratory.

Introduction

All over the world, chemistry educators and researchers deem introductory chemistry laboratory instruction as an essential component of tertiary level chemistry education. Despite this enthusiastic support and the many benefits attributed to the academic laboratory experience, there is a standing debate pertaining its purpose and its effectiveness in accomplishing desired learning outcomes. Already in 1915, in an article with a rather direct title - problems in the experimental pedagogy of chemistry - Spears called attention to the need for systematic investigations to support pedagogical decisions in the experimental instruction of chemistry. Over the past century much has been said and written, with several review reports examining research on learning in the academic chemistry laboratory (e.g. Hofstein & Lunetta, 2004; Nakhleh, Polles, & Malina, 2003; Reid & Shad, 2007). Nonetheless, a common stance expressed by many researchers and review authors is that we simply do not know enough about learning of chemistry in academic experimental environments, or more

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uncompromisingly forthright that the "*learning environment of the science laboratory is one of the areas that has been neglected by researchers*" (Hofstein, Cohen, & Lazarowitz, 1996). It is no surprise that the inherent merit of laboratory instruction has been called to question in the literature (Hawkes, 2004; Hilosky, Sutman, & Schmuckler, 1998; Reid & Shad, 2007). Notwithstanding, Hodson makes an opportune clarification: criticism of laboratory instruction is "*not so much an attack on practical work per se as a criticism of the kind of practical work we choose to do, and the way in which we implement it*" (2005, p. 30). At the same time that researchers concur that "*precious little evidence exists that such instruction provides a useful function in the way(s) students learn chemistry*" (Elliott, Stewart, & Lagowski, 2008, p. 145), instruction continues to be guided by opinions or personal theories conveniently accompanied by the assumption things work just well the way they are. Paradoxically, those most directly involved with chemistry laboratory instruction often seem unaware of this profound debate.

The goals of this chapter are: (1) to highlight the current need for more educational research that focuses specifically on learning chemistry in laboratory environments in tertiary education; (2) to briefly describe our systematic efforts to contribute in closing this gap; (3) to advance the proposition of using naturalistic inquiry - specifically phenomenology - to conduct this type of research; and (4) to exemplify the use of phenomenology by summarizing some of our findings.

Research on learning in the laboratory at tertiary level

We advocate research that is specific to learning chemistry in the academic laboratory at tertiary level. Our understanding of learning at secondary level may be very informative; however, its direct transfer to tertiary education is not warranted. Learners at these two levels are at substantially different maturity stages and at very different levels in their socialization processes. In like manner, they are dissimilar in terms of their cognitive development, motivation, and expectations. Although, college students are an extract of the top academic secondary performers, their instructors are scientists with expertise in the subject yet pedagogically untrained. Learning chemistry, especially in the lab, is different from learning other sciences. In order to make sense of chemistry experimental data, students need to grasp theories based on atoms and their bonds for which they do not have immediate tangible references. Adopting a sub-microscopic perspective is a prerequisite to gain a useful perception of the essence of chemistry, thus an intrinsic difficulty stemming from the uniqueness of chemistry as an object of study (Floriano, Reiners, Markic, & Avitabile, 2009). As Hodson noted the "*skills involved in observing the behaviour of aquarium fish have little relevance in observing the behaviour of chemicals on heating*" (1992, p. 124). Despite informative, what we may know from research on learning other sciences is not necessarily applicable to learning experimentally in chemistry. Lastly, the chemistry laboratory extensive complexity and information-rich nature have been recognised to pose unique challenges and affordances when compared to other environments such as the classroom (Nakhleh, 1994). Regardless of the instructional approach, the nature and extend of students' interactions with the activities, peers, instructors, and glassware, instruments, and materials in the chemistry laboratory and the wide variety of variables that affect student learning create a multitude of unique learning instantiations that cannot take place in a lecture hall.

By all appearances, agreement within the chemistry education research community points at the need of sound research that can significantly increase understanding of the role of laboratory instruction in learning chemistry. A recent report (Singer, Nielsen, & Schweingruber, 2012) that reviews the current state of the art in research on college science education concludes categorically "*the role of the chemistry laboratory in student learning has gone largely unexamined*" (p. 6-11). A study currently under way in our group provides further evidence of this research gap: the average yearly number of research articles published over the past 25 years is only slightly above five. This rather meagre research production does not match the presumed centrality of the laboratory experience in the learning of chemistry. Furthermore, other bibliometric indicators such as citation connectivity and author productivity suggest there are deeper issues than the bare quantity of research. For instance, 86 per cent of the authors in the database published a one-off paper and only six per cent have contributed more than two. Two arguments come to mind: first, there is a void of expertise with few groups dedicated to research in this field, and second, understanding of particular topics can hardly be thorough when investigation is not pursued over prolonged times and multiple studies. These issues impact the research agenda since addressing big, challenging, tough ideas or research questions requires time and developed expertise. Preliminarily, this study suggests predominance of studies that utilise a piecemeal approach, focus on the assessment of the implementation of pedagogies or short interventions, and favour experimental approaches linked to academic performance. Signs over the past decade suggest a more favourable trend with authors publishing more, more published work on singular topics, inclusion of qualitative approaches, and consideration of non-cognitive variables and outcomes. However, only time will tell whether this trend is an artefact of a small number of doctoral students temporarily choosing this field and who after completing their degree will move on to different research interests.

Fundamentals of our research approach

Our group has worked on building a dedicated research programme to contribute in closing the research gap in learning in the laboratory at tertiary level. In this section we highlight the pillars supporting the structure of this programme. From the onset, we have embraced the research focus on learning suggested by other researchers (Hofstein & Lunetta, 1982; Nakhleh, 2002). Nakhleh and collaborators underscored that "*the goal of research is to thoroughly understand what* *occurs in the laboratory and then work on revising curriculum and pedagogy*" (p. 78). Chang and Lederman (1994) reckoned the complexity of the science laboratory and the many variables simultaneously affecting learning contradict the assumption that altering just one variable would significantly affect students' achievement. These perspectives invite work to gather a fundamental and comprehensive understanding of broader aspects of the laboratory experience, such as metacognition or more specifically learning, as prerequisite to engaging in pedagogical modifications. We maintain learning happens in all laboratory environments (i.e. instructional approaches), certainly, in some more efficiently than others. Our interest centres on understanding and distilling the active ingredients of learning in its broad meaning in multiple and diverse environments. Once characterised, practitioners may adopt and adapt these active ingredients observing the idiosyncrasies of their own contexts, without resorting to prescriptive pedagogical formats.

Already in 1982, Hofstein and Lunetta underscored the effect methodological and design weaknesses exert on research on learning in the lab. In 1994, Lazarowitz and Tamir suggested varied research designs were needed to advance the field at the same time they deemed their implementation challenging. Issues with methodological approaches were raised by Hodson as well who pointed out that "*a definitive answer to our questions about the pedagogic value of laboratory work*" was unlikely unless research focused more sharply on what students actually do in the laboratory (1990, p. 39). Discipline-based chemistry education continues to evolve in response to the emergence of new and more engaged research questions and problems. In recent years, this trend has encouraged the advent of mixed-methods designs, as well as purely naturalistic or qualitative studies. Nakhleh and collaborators described the new focus in laboratory research as "*the notion that the effect or value of the laboratory experience might not be measurable in a quantitative sense*" (2002, p. 78).

We summarize the above in two overarching, foundational ideas. First, the broad, big idea of seeking an enhanced understanding of what happens in academic laboratory environments to shed light on how learning takes place (or not) instead of focusing on fragmented and isolated variables and their effect on content specific outcomes. And second, a methodological perspective that calls for the use of naturalistic inquiry approaches that are better suited to address questions aimed at understanding how learning occurs. These foundational ideas underlie a series of premises that frame our research programme on learning in the chemistry laboratory at college level. Table 1 lists a set of representative building blocks of this programme. As noted above, methodological approximations have posed a particular challenge in the study of experimental learning. In our pursuit of understanding learning in the chemistry laboratory we have become more engaged with naturalistic approaches. The following section advances the rationale behind our proposition of using naturalistic inquiry - specifically phenomenology - to conduct research on learning in laboratory environments.

Table 1. Selected building blocks of the research programme

Building block	Brief description
Orthogonality between instruction and research involvement	To the extent possible, research and instruction engagement are maintained separate. The programme aims at investigating learning environments in which the team is not directly engaged in instruction or has vested interests. Close proximity to the instructional programme may hinder one's unbiased consideration of research data
Use of multiple research approaches	In response to the complexity of the learning environment, the programme uses diverse research tools. Given the broad nature of research aims, it is driven by naturalistic approaches.
Focus on the enacted curriculum instead of the designed curriculum	The explicit purpose of studying what the students are actually doing and how this may influence learning defines the programme's focus on the enacted curriculum.
Investigation of multiple laboratory programmes in their natural expression	Our premise is that learning may happen regardless of the instructional approaches. Additionally, this allows us to study programmes that are in place and have stabilised as opposed to studying altered experiences where innovation enthusiasm may colour findings.
Approach through participants' lens	The programme combines students and teaching assistants or demonstrators as participants and is interested in the learning of both groups.
Focus on learning as opposed to teaching	Our purpose is to complement the work done by others that focuses on instructional design and implementation.

Phenomenology as a theoretical framework to study learning in the college chemistry laboratory

Differentiating experimental (quantitative) from naturalistic (qualitative) methods seems more straightforward than defining the varied naturalistic approaches. This is due, at least in part, to the variety of taxonomies in the literature (Creswell, 2009; Patton, 2002; Van Manen, 1990). We adhere to Patton's suggestion to frame approaches based on the type of questions they address. From this perspective, phenomenology attends to the following question: "*What is the meaning, structure, and essence of the lived experience of this phenomenon for this person or group of people?*" (p. 104) Here essence refers to the "*core meaning mutually understood through a phenomenon commonly experienced.*" (Patton, 2002, p. 106). Van Manen (1990) encapsulates this definition more succinctly: "*Phenomenology asks… for that which makes a some-"thing" what it is—and without which it could not be what it is*". Phenomenology on a whole is a philosophical tradition as much as a methodology. In this sense, we align again with the pragmatism favoured by Patton (2004) for whom qualitative methods are mature and stand-alone as much as quantitative methods. Although the philosophical tenets of phenomenology inform our practice, we stir away from entanglement in the philosophical discussions surrounding the tradition and use phenomenology as an inquiry methodology.

Three factors, important to researchers as well as to consumers of phenomenological research, define phenomenology as opposed to studies that take a phenomenological perspective. First, essence is to phenomenology what culture is to ethnography. If the premise of essence is doubted, then the possibility of phenomenology is denied. In our view, a phenomenological study must explicitly set out to investigate the essence of a phenomenon. Second, phenomenology investigates the lived experience: we can only know what we experience. Therefore, it cannot be second-hand and relies on in-depth interviews through which the participant describes, explicates, and interprets their experience, thereby bringing the experience to their own awareness or consciousness. Third, phenomenology is retrospective, that is, surfacing of the experience to consciousness shall not occur while the experience in underway. Interviews are not to be an introspective exercise. In addition to clearly teasing out phenomenological studies from those that simply take a phenomenological perspective, these three factors carry methodological implications. For instance, as researchers we do not disrupt participants during their living of the experience since this would taint phenomenological data, and these data are gathered exclusively through in depth, open interviews only after the conclusion of the experience.

Chemical education research aims at thoroughly understanding what occurs within chemistry learning environments and how it occurs, specifically in this case, in the chemistry laboratory. This thorough understanding requires the realization that the value and impact of the laboratory experience may not be measureable in the traditional quantitative sense (Nakhleh, 2002). Furthermore, the complexities of this environment involve a vast number of cognitive and non-cognitive variables, interactions, and components that, while achieving more traditional goals (psychomotor and procedural), result too in a holistic experience that affects students in multiple other levels, particularly in the affective dimension. Once this thorough understanding has been sufficiently developed, informed curriculum and pedagogical changes can be designed to effectively promote the realization of the true potential of the chemistry laboratory. We believe current paradigms tend to focus on studying the effectiveness of instructional interventions in the laboratory that derive from researchers or instructors' reactions to the common urge for improved instruction. However, from our point of view a sound understanding of learning should precede interventions, and researching learning should occur through the perspective of those experiencing learning. This proposed shift in focus leads to a corresponding need for new research methodologies and it is here where we make a case for using phenomenology. Although in 2007 Casey tangentially introduced this argument no other groups have ventured in its use for the purpose of studying learning in the college chemistry laboratory.

Naturalistic researchers approach settings without preconceived hypotheses or theories to be proven or falsified. Understanding and theories emerge from and are grounded in fieldwork and data. From an epistemological sense, phenomenology focuses on revealing meaning, uncovering the internal and invariant essence of a phenomenon rather than developing an abstract theory or arguing a point. This facet on its own constitutes a methodological strength in alignment with the goal of thoroughly understanding learning as it occurs within the laboratory environment. Phenomenology, as an inductive and descriptive research tool, offers unique perspective in the tertiary chemistry laboratories because the discovery of knowledge requires the development of meaning in a given context. Thus, by understanding how students interact with reality and give it meaning within this social context we strive to gain a realistic perspective of learning in the laboratory. The complexities of the laboratory environment limit methods in their ability to measure what occurs within such environment. We contend phenomenology's true power lays in the fact that it accounts for the social and environmental context of developing meaning through a deep, rich description of participants' lived experiences, something that cannot easily be attained through experimental approaches or even other qualitative methods.

An additional affordance of phenomenology is that beyond the thick, rich description of the phenomenon, it provides students a voice. Educational research that views students as "subjects" and is designed in a way that some action is performed onto them may gather an incomplete or skewed picture of the experience. Although useful in many senses, Van Kaam argues that, when imposed on 'subjects', experimental studies "*may distort rather than disclose a given behaviour through an imposition of restricted theoretical constructs on the full meaning and richness of human behaviour*" (as cited by Moustakas, 1994, p. 12). In educational phenomenological studies, the students are participants in research rather than subjects of research. The structure and essence is reached as a result of co-creation between the participants and the researchers. Rather than acting passively, students relive and relate the experience, thus they exercise their voice and they actively contribute to the research. The researchers work alongside the participants to recreate the lived experience and to reduce it through the textural and structural analyses to uncover its essence. Phenomenology requires co-constitutionality between the participants and researchers where the essence forms from meanings comprised of a blend of those articulated by the participant and researcher. This aligns with our research intent to focus on the learner and learning.

Though phenomenologists' global aim is the same - distilling the essence of a phenomenon - they may resort to procedural variants that better fit their perspectives. We adhere to the phenomenological analysis put forward by

Moustakas (1994) with only minor modifications. Our rationale and the procedural details have been reported elsewhere (Sandi-Urena, Cooper, & Gatlin, 2011; Chopra, O'Connor, Pancho, Chrzanowski, & Sandi-Urena, 2016).

Sample phenomenological studies on learning in the chemistry college laboratory

We have used our phenomenological approach to investigate the experiences of students and their teaching assistants in three general chemistry laboratory programmes. A study of a fourth programme is underway. These studies do not intend to be archetypical but we are confident they reflect the potential of phenomenology as a tool to research the complex environment of the chemistry academic laboratory. For the sake of simplicity, we categorise these programmes as more traditional - experiences that approximate verification labs and less traditional - labs purposefully designed to take distance from verification labs.

Our first report derived from a sequential explanatory mixed-methods study whose goal was to probe the effectiveness of a cooperative, project-based general chemistry laboratory (less-traditional type) to support student learning (Sandi-Urena, Cooper, Gatlin, & Bhattacharyya, 2011). The qualitative component was designed to further understanding of the quantitative findings that showed students increased their ability and metacognitive strategies in solving online ill-structured chemistry problems (Sandi-Urena, Cooper, & Stevens, 2012). Phenomenological data reduction, analysis, and interpretation of in-depth, open-ended interviews produced an outcome space composed of three dimensions: affective response, understanding of the learning experience, and strategic response.

The affective response describes students' reaction to an environment that is unfamiliar despite the programme's efforts to inform them. This unfamiliarity and mismatch of expectations creates an affective and cognitive imbalance students resolve over the first few weeks in the lab. Initially, the affective response is expressed as confusion and frustration mixed with varying degrees of rejection. However, as these feelings recede, the struggle with the nature of the lab format diminishes and "acceptance" settles in.

The second dimension, understanding of the learning experience, refers to the evolution of the initial cognitive imbalance: Participants advance their understanding of how things work in a cooperative, problem-based environment. This understanding emerges from experiencing the dynamics and not from being informed externally, that is, this understanding is constructed experientially and not accepted from a perceived authority. Students' understanding is reflected in their ability to accurately describe the laboratory paradigm: They describe the role of the teaching assistant and their lab team, they justify the absence of direct procedural instruction, and compare their experience with their perception of doing research. As is the case with the affective dimension, reaching this understanding comes at different times and to different extent for different students.

The strategic response postulates that once the students accept and understand the dynamics and workings of cooperative, project-based learning, their attention and intention turn to developing and implementing the activities and skills necessary to succeed in this environment. With a better handle of the affective and cognitive imbalance, students describe their engagement in a series of skills and activities that fall in the three categories of regulatory metacognition: planning, monitoring and evaluating (Schraw, Crippen, & Hartley, 2006). Figuring out - a theme common in the narrative of the participants - is the driving force that sustains the deployment of these skills to meet the demands of the learning experience. In other words, the learning environment induces this metacognitive behaviour. We have argued that taking charge is the overarching factor holding the experience together at the same time that it is a requisite for successfully completing the programme. Aware or not, students drive their actions and decisions towards that goal. Progressively, students move from their initial stance where learning is something done onto them to taking responsibility of their learning. To gain control of their learning they continually elaborate on the three dimensions above.

We believe who teaches matters; furthermore, we support the stance the instructor is the most influential factor in the laboratory experience (Lazarowitz & Tamir, 1994), and that failure to consider their role derails progress in advancing learning in the laboratory (Herrington & Nakhleh, 2003). Differences abound across types of institutions and countries in terms of who is assigned instructor's duties. In the US, research institutions use doctoral chemistry students as graduate teaching assistants (GTAs) while the tendency at liberal colleges is to employ faculty. Participation of teaching assistants introduces additional complexity in the enactment of the designed curriculum (Roehrig, Luft, Kurdziel, & Turner, 2003). Therefore, we pursue a naturalistic approach of learning in the laboratory as it occurs and not as it was meant to happen, and regard the GTAs as active participants in the learning environment. New training proposals have emerged based on providing pedagogical knowledge to incoming graduate students. Often they operate under the prevalent instrumentalist view of the GTA; the underlying assumption being that knowing about learning theories and teaching strategies transforms them into effective teachers over the course of a short period of time.

We have argued that graduate students' instructional decision-making is closely linked to their self-image as teaching assistants (Sandi-Urena & Gatlin, 2013). Concomitantly, GTA self-image greatly influences students' laboratory experience and learning. Conceptualisation of the construction of a self-image as instructor and its impact on the learning environment emerged from our prior phenomenological work. Two independent phenomenologies of GTAs engaged in two dissimilar laboratory programs - one expository-based (Sandi-Urena & Gatlin, 2012), the other inquiry-based (Sandi-Urena, Cooper, & Gatlin, 2011) -

shed light on the essence of these GTAs' experiences and the nature of gains and benefits available to them.

We have introduced a model that describes factors and their interactions that may catalyse graduate students' development or transformation of their GTA self-image in order to accomplish specific goals of laboratory instruction. This model invites faculty in charge of laboratory programmes to reconsider GTA participation in instruction and their training and support in a new light. In this model, the GTA self-image determines fidelity of implementation of the learning environment while GTA self-image is shaped by graduate students' beliefs about the nature of knowledge and their beliefs about the nature of laboratory instruction. Instead of focusing exclusively on what and how to teach, GTA training and support programmes may target these two factors in a way that is conducive to develop a self-image in alignment with the program's instructional objectives. We view this approach as adding a new dimension to GTA training: why to teach. Training programs that focus on what to teach and how to teach may succeed in getting GTAs to adhere to overt expected behaviours while under close monitoring. But as suggested by Goertzen and collaborators (2010): "*helping TAs learn to ask questions will not necessarily help them share [...] motives for questioning*". To address this issue, we believe training and support need to incorporate graduate students' beliefs about the nature of knowledge and the nature of laboratory instruction, that is, mediating the development of a GTA self-image consistent with the goals of the lab programme.

Conclusion

In this paper, we have argued there is a substantial gap in research on learning in the tertiary level chemistry laboratory. Not only is there insufficient research done but also there are questions about the developed expertise in the research community and the depth in the topics researched. We have not commented the qualities of research but borrow Domin's expression in his review of laboratory articles: "*The amount of credence one places on these findings is reserved for the reader*" (1999, p. 546). This research gap is in evident contradiction with the professed centrality of the laboratory experience in chemistry education. We understand it may stem from the intrinsic and methodological challenges of investigating such a complex learning environment. We have briefly described our modest attempts to contribute in addressing this gap, particularly, utilising phenomenological approaches. We hope this paper encourages others to venture into conducting research in this fertile field and to consider naturalistic approaches for this purpose.

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