Laboratory-related competences at university level: Systematizing empirical literature and expert validation

Hendra Y. Agustian, Jan Alexis Nielsen, Maja Ingerslev Pedersen

Department of Science Education, University of Copenhagen

In this paper, we aim to summarize salient findings from a systematic review of empirical literature in post-secondary chemistry laboratory education and expert validation of the results. A part of a larger research project aimed at improving learning in the laboratory, the review was conducted with a purpose of characterizing learning outcomes associated with teaching laboratories. We focus our analysis of 355 empirical studies on evidence for learning substantiated through various theoretical, pedagogical, and methodological approaches. Through the lens of competence acquisition and development, we have characterized five large clusters of learning outcomes pertaining to multifarious domains of learning, viz. *experimental competence, conceptual learning, higher-order thinking skills, affective outcomes, and transversal competence. These findings laid a foundation for the subsequent expert validation involving 31 professors and associate professors teaching laboratory courses in chemistry and pharmaceutical sciences. In our reviewed studies, we found that learning in the chemistry laboratory is distinctively multidimensional, encompassing students' cognition, affect, conation, and psychomotor domain. Evidence has also been shown for learning outcomes pertaining to the social and epistemic domains. However, we argue that the manner in which those domains have been substantiated still necessitates integration. Our systematized expert validation concurs with some of these results, with further elaboration and addition emerging from the faculty members' experience and expertise. Implications for laboratory education research were discussed.*

Keywords: Laboratory work in science, learning, higher education

INTRODUCTION

Educational values of teaching laboratories have been a subject of contestation and justification among stakeholders of higher science education. On one hand, proponents of this mode of science instruction herald their value from viewpoints of competence required of science graduates, identity as a scientist, and affective domain. On the other hand, critics question the actual learning outcomes of individual laboratory exercise supposedly superior to less expensive and labor-intensive modes such as lectures and expert demonstrations. While debates are ongoing and discourse developing, three options for laboratory education researchers and curriculum designers posited back in 1993 are still up for a challenge: (1) to continue with labs as they are, (2) to drop the entire (wet) lab course (and possibly replace it with a virtual alternative), or (3) to try to improve (Pickering, 1993). In our research project, we strive for the third option. In pursuit of evidence for learning in the laboratory, also responding to Bretz (2019) and Seery (2020), we have conducted a systematic review of empirical literature aimed to characterize learning in the laboratory at university level, which was subsequently validated and further elaborated by faculty members teaching chemistry and pharmaceutical sciences.

METHOD

Systematic Review

The entire ERIC and Web of Science databases were searched for publications related to laboratory work and student learning. More details on the search strings, inclusion and exclusion criteria, study selection, quality assessment, data extraction and analysis are elaborated in the upcoming publication (Agustian et al., forthcoming). We selected 355 articles out of the initial 55572 into our review, with the final criteria being empirical studies in chemistry laboratory education context at university level. Each study was characterized by its aims, theoretical or pedagogical frameworks, methods and methodologies, research instruments, specifications of participants, intervention (wherever available), and results explicating student learning outcomes. Subsequently, it was critically appraised for the quality of the study design, results, relevance, and applicability in light of the review question. The studies were analyzed by firstly coding the results section for all types of student learning outcomes, including key competences. These codes were combined into themes, whereby a single publication could be present in different themes. Further analysis led to refined sub-themes.

Expert Validation

The findings from the aforementioned systematic review laid a foundation for the subsequent expert validation involving 31 professors and associate professors teaching laboratory courses in chemistry and pharmaceutical sciences. Four cycles of focus group interviews were conducted to discuss the five themes (also referred to as clusters) associated with learning in the laboratory. Thematic analysis of the verbatim transcript was used to elucidate correspondence, relatability, and exemplification of each and every learning outcome. Perspective of competence development in higher education was used from which discussions were illuminated.

RESULTS

Experimental competences

Chief to the substantiation of learning outcomes in teaching laboratories is the acquisition and development of experimental competences, which concerns processes and actions related to a scientist's work in the laboratory. The reviewed studies demonstrate that students learn a range of general to specific laboratory techniques, from basic skills (*eg.* pipetting) to advanced techniques (*eg.* LC-MS/MS analysis of metabolic pathways). We are particularly interested in how laboratory activities in an inquiry curriculum enhance student learning and we have found supporting evidence. Specifically, such instruction increases students' experimental competence, independence, confidence, and reflection. This is even more strongly pronounced in a laboratory instruction that represents authentic research experiences. Of all outcomes in this cluster, we maintain that designing an experiment is of the highest order.

Disciplinary learning

The majority of studies in our review pertain to conceptual learning, academic achievement, theory-practice connection, and students' mastery of a discipline as a focal point of their investigation. There is substantial evidence that more open-ended and investigative laboratory experiences increase students' conceptual understanding. However, the caveat is when they are entirely unguided, no significant effect is shown. If anything, they may lead to misconceptions. To facilitate the acquisition of conceptual knowledge, as well as experimental skills, pre-laboratory work is a prerequisite. The longstanding conundrum of connecting laboratory exercise to its underlying theory is also a recurring theme. Various approaches to resolving this problem include pre-laboratory videos and producing own data. The overarching competence related to this outcome is students' development towards mastering chemistry as a discipline.

Affective outcomes

Laboratory work has been demonstrated to generate various affective outcomes, including attitudes to science, interest and engagement, self-efficacy, motivation, identity development, and self-regulation. The extent to which they have been investigated varies, and we argue that the conceptualization of some of these constructs requires more rigorous theoretical and methodological grounding. That being said, our review reasserts the value of laboratory instruction from an affective perspective.

Higher-order cognition and epistemic learning

A number of studies provide ample evidence that students develop several competences belonging to higher-order cognition, *viz.* problem solving, critical thinking, and metacognition. These are prominent in research-based and problem-based curricula, as well as industrially-situated laboratory. Likewise, some of these approaches to instruction afford opportunities to reflect on important epistemological aspects of laboratory work and the knowledge it purports to generate.

Transversal competences

Apart from discipline-specific knowledge and skills, laboratory work also facilitates the acquisition of transversal competences. Some of their proxies of characteristics include transferability and cross-functionality. They also typically relate to social and interpersonal relations. Our review demonstrates that students acquire skills related to collaboration, communication, reasoning and reflection, writing, and argumentation.

Validation

Data are still being analyzed, but preliminary findings generally concur with the five clusters of learning outcomes resulted from our review, with a scope for further elaboration and exemplification. Admittedly, some of these competences are not easily realized in the current laboratory curriculum, but these findings have been regarded as an inspiration for faculty members in their attempt at improving laboratory instruction.

DISCUSSION AND CONCLUSIONS

Our synthesis demonstrates that learning in the laboratory is distinctively multidimensional. The multifarious types of learning outcomes substantiated through laboratory exercise encompass several domains of learning and manifest in a range of constructs that lend themselves to cognition, affect, conation, psychomotor, and epistemic dimension of science.

Pertaining to some of these domains, there seems to be a stratification, from lower- to higher-order, basic to advanced, concrete to abstract, general to specific, naïve to sophisticated understanding, and isolated to integrated. However, the manner in which those learning domains have been substantiated still necessitates integration.

Unsurprisingly, chemistry-specific outcomes are strongly represented, but there is need for more focus on higher-order cognition. There is a tendency that the psychomotor domain is not assessed adequately. Nevertheless, considering the reality of career in science where basic practical skills such as titration may be deemed obsolete, we wonder if the design for learning and corresponding assessment should be directed towards higher-order experimental competences. Regarding the affective domain, there is an ample scope for more theoretical grounding in the substantiation of constructs such as interest and engagement. Likewise, a need for more research into the social and epistemic dimensions of learning in the lab is also identified.

Preliminary findings from the expert validation are generally aligned with the results from the systematic review. From the viewpoint of the faculty members' expertise and experience, it is clear that the notion of competence development is pertinent to the acquisition of various outcomes mentioned above. These insights are considered useful in helping them revisit and potentially redesign laboratory courses they teach. We argue that laboratory educators also need to rethink the ways in which learning is assessed in the laboratory, should they wish to improve the existing practice of laboratory education in university settings.

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