ACTION RESEARCH ON ELECTROCHEMISTRY LEARNING. CONCEPTUAL MODELLING INTERVENTION TO PROMOTE DISCIPLINARY UNDERSTANDING, SCIENTIFIC INQUIRY AND REASONING

M. Orozco [1]
University of Twente
Enschede, The Netherlands
ORCID 0000-0003-3101-0247

M. Boon
University of Twente
Enschede, The Netherlands
ORCID 0000-0003-2492-2854

A. Susarrey Arce
University of Twente
Enschede, The Netherlands
ORCID 0000-0003-2572-223X

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[1] *Dr. ir. Mariana Orozco*
m.orozco@utwente.nl

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ABSTRACT

Students in engineering-science programmes often struggle with theoretical concepts, while they tend to adopt a surface approach to learning. We suggest that this can be tackled by promoting a specific higher-order thinking skill (HOTS) that enables drawing connections between physical phenomena and theoretical concepts representing them. We designed an intervention to support students in achieving deep insight into electrochemical phenomena, while developing this HOTS. Such intervention aims to scaffold students' learning and development by introducing conceptual modelling as an essential thinking skill of engineering-scientists, and as a strategy to build scientific understanding of natural phenomena. Therefore, conceptual modelling constitutes a main learning objective of this novel course. This paper reports an empirical investigation into how students deal with concepts and complexity, and to what extent the intervention has any measurable effects on the learning outcomes. This phenomenological investigation integrates considerations from various disciplines, and relies on multiple data sources, i.e., students' documents (lab journals and reports), observations of students in action (in discussions with their tutors and while performing lab experiments), and video stimulated-recall interviews. The results show little effect of the intervention, as implemented, suggesting how challenging it is for students (and instructors) to shift from traditional learning-and-teaching approaches, towards an epistemology of knowledge construction for specific problems. The findings are informative for revision of the intervention and generate specific recommendations. Concurrently, our operationalisation of the conceptual framework proves powerful in detecting qualitative differences in HOTS. Plausible implications for research and educational practice in science-engineering education are discussed.

1 INTRODUCTION

1.1 Background, building blocks and overview

Electrochemistry is an essential scientific and practical domain within Chemical Science Engineering (CSE) [1]. Concurrently, students often struggle with conceptual aspects [2] , and many adopt a surface approach to learning [3].

An action research [4] project was conducted to design and implement a pedagogical intervention aiming to support students in achieving deep insight into electrochemical phenomena, while developing higher-order thinking skills [2]. This new 'thinking as a scientific researcher' course[2] taps on inquiry-based learning (IBL) principles [5], while approaching the teaching of thinking in an explicit and content-related fashion, according to a mixed general-infusion approach [6]. Importantly,

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[2] The laboratory experience is used as a means of discovery and new theorisation, rather than to confirm given theories empirically (as more traditional lab courses often do). In short, the aim is to promote a different epistemology concerning the role and contribution of science to problem-solving, that is not commonly conveyed in engineering education.

students' learning and development was scaffolded by conceptual modelling [7,8], as a strategy for conducting scientific research that seeks to promote the understanding of natural phenomena. Conceptual modelling is considered an essential reasoning ability of (engineering) scientists and is a chief learning objective of this new course [2]. It is proposed that the conceptual modelling skill can assist students in understanding and theorising (electrochemical) phenomena, so that they will be able to creatively think about such phenomena in new technological problem-solving contexts.

Our empirical educational research witnessed the implementation of this intervention [2]. This phenomenological investigation sought to explore (RQ1) how students learn electrochemistry under the intervention as implemented and in terms of indicators of progress in reasoning, to describe (RQ2) in what ways the student learning is embedded in the learning environment, and to evaluate (RQ3) to what extent the intervention has any measurable effect on the learning outcomes.

This interdisciplinary project, including the instructional design of the course and the educational research design, integrates considerations from Chemical Science, Philosophy of Science in Practice, and Education Sciences. This empirical paper builds on our conceptual work [2], where we elaborate on the relevance of electrochemistry in engineering-science education, and we present an overarching methodological and theoretical framework, as well as a a thorough description of the pedagogical intervention. The present contribution further introduces our analytical framework, which is based on levels of complexity [9] and on recurrent difficulties [10].

1.2 Levels of complexity

In line with our theoretical framework [2], we are interested in qualitative differences in learning; these are best observed in connection to the content, and in both the process and the outcomes of learning [11]. The 'levels of complexity' framework [9] appears appropriate as analytic tool because it takes a situated cognition perspective on learning and cognitive development (which aligns with the IBL approach), and it is developed within a comparable empirical context.

The original framework proposes 8 categories denoting increasing complexity. The first category group refers to 'objects' the students use in the laboratory, their aspects, and their properties[3]. The second category group refers to covariations of aspects and properties of objects and materials[4]. First, we had to grasp in what ways one category is more complex than the preceding one and what it takes to move from one category level to the next. Our reading is that growing complexity means

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[3] During the operationalisation of Wenzel's original framework, we broadened 'objects' to include any materials (e.g., electrolytes, salts, buffer solutions) and added a crucial feature, i.e., their purpose. These modifications emerged during our initial data analysis and, therefore, they are part of our research findings (which were engaged in the fine tuning of the analytical tool).

[4] These (co)variations, we add, are not just present or absent. They can be accompanied by a qualifier indicating an effect size and a description of the conditions for the covariation to occur

increasing generalisation, systematisation, acknowledgement of what is contingent and what is stable, connectivity of associations, and covariation (not causality). Finally, we operationalised those categories into an analytic tool that resonates with our particular empirical context. A summary is presented in the methods section.

1.3 Recurrent difficulties

Prior research on teaching and learning Electrochemistry [10] proposes a set of known recurrent difficulties (KRD) experienced by students and teachers. Such KRD are rote application of concepts and algorithms, use of multiple definitions/meanings (from different contexts[5]), use of multiple or hybrid models, wrong interpretations of language, too early connection of labels to meaning, and misleading analogy. To this list, we added 'attribution' to consider groundless or wrong attribution of effect (e.g., causality, mediation, interaction, contribution), as often observed in our experience. These KRD allow one to think about the plausible cause of difficulties, for which knowledge of the disciplinary content involved is required.

2 METHODOLOGY

The research methodology is phenomenological, i.e., interested in the subjects' experiences, next to their performances. Therefore, in seeking methodological consistency [4], we choose to use qualitative methods of data collection and analysis. The project has three educational research purposes (i.e., to explore, to describe, and to evaluate) which were translated into distinctive research questions, as presented in Section 1.1.

2.1 Empirical context

The new lab course consisted of 5 practicums, each to understand a particular electrochemical phenomenon, while addressing an electrochemical question. The students worked in groups of 3 and their learning process was facilitated by learning assistants (LAs). In the preparatory and reflective work around each practicum, the conceptual modelling activity was supported by the B&K method [7], as a cognitive scaffold for the learning and persistent use of conceptual modelling as a conducive scientific way of reasoning. The sustained and effective use of this scaffold was taken as an indicator of the attained level of cognitive skill development [2].

2.2 Data collection

For this study, we selected practicum 2 (about a specific electrochemical cell) and practicum 5 (about cyclic voltammetry) for being particularly challenging, distributed

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[5] Based on a historical analysis on 'electrochemical concepts and their meaning in context', i.e., the phenomenological, the particulate, the measurement, and the thermodynamic contexts. This analysis is not to fragmentate what the Conceptual Modelling approach aims to unite (by organising it coherently), but to understand the epistemological difficulty and complexity that electrochemistry represents for students, teachers, and researchers.

in time, and integrative. For additional details on the content and objectives of these practicums, see our conceptual paper [2].

Twenty students (out of 45) consented to participate in this investigation, among whom 8 also accepted to be interviewed. Their data was considered at an individual level. Furthermore, all students had been grouped into 15 work groups of 3. This distribution resulted into 2 full participating groups, whose data was analysed in an aggregated fashion, according to a case study design [12].

The multiple sources of data were (i) documents, i.e., intermediate, and final lab journals, and group reports, (ii) video recordings and transcripts of observed meetings among students and their LAs, (iii) video recordings of students while performing their lab experiments, and (iv) audio recordings and transcripts of video stimulated-recall interviews. The pieces of data were matched to individual students and to groups, allowing for triangulation of the findings.

2.3 Data analysis

In line with the phenomenological approach to research, we were interested in the data that captures subjects' experiences, and further in how various sources of data speak to each other. A case-study logic[6] was used, seeking validity in terms of the depth and robustness of the analytical work [12,13] .

The usable data was prioritised according to availability and richness criteria. The thematic coding[7] relied on the categories in Table 1. After open, axial, and selective coding of the data sources by project group (2 cases), we integrated further pieces by student (8 individual subjects) until we estimated that data saturation had been reached.

Table 1. Summary of the operationalised 'levels of complexity'

Levels	**Description**
Objects	construction of stable figure-ground distinctions
Aspects	links between objects and/or identification of specific features
Properties	construction of classes of objects, based on common/different aspects
Purpose	the intended purpose, function or use of objects and other materials
Variations	changes relating two or more aspects/properties of objects/materials
Operations	systematic variation of objects according to their aspects
Events	links between some stable properties of the same/different classes of

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[6] A case-study logic contrasts to a sampling logic, i.e., rather than seeking statistical representativeness, the validity of the conclusions resides in the quality of the analysis, which seek explanatory connections and theoretical replication until data saturation.

[7] To some extent, coding the data according to these categories was interpretative. Often the attribution of a character (e.g., specificity/generality, contingency/stability, concreteness/abstraction, or disorder/organisation) to variations had not been made explicit by the subjects and required a reading of latent meanings (which was supported by the conversational context and/or warrants from the same subject in another data source).

	objects
Programmes	systematic variation of a property according to other stable properties
Principles	construction of stable co-variations of pairs of properties for classes of contexts
Connections	links between several principles with the same/different variable properties
Networks	systematic variation of a principle according to other principles
Systems	construction of stable networks of variable principles

3 RESULTS

3.1 Levels of complexity

Students ’skip’ several levels (e.g., passage from *aspects* to *events*), i.e., rather than 'true discovery', the students appealed to prior knowledge or by-pass the instructional sequence by searching on the Internet. Also, there was much centrality of *objects and materials*, even more than the phenomenon under study (which was often not made explicit). Moreover, students’ reasoning and comprehension seems to benefit when they consider the *purpose* or function of the materials in the experimental setup; they often did this spontaneously, while several difficulties appear to stem from unclear purposes. Furthermore, the students often played attention to *aspects of covariations*, mainly in terms of quality and quantity (e.g., an effect is stronger, a reaction is slower). Causality or directionality were only denoted.

In all, the students seldom went beyond the level of *events*. No measurable[8] growth over time was observed (neither within each experiment, nor between experiments), i.e., students seem to stagnate at a relatively low level.

3.2 Recurrent difficulties

The biggest category is the *rote application of concepts and algorithms*, which seems to give students a false sense of understanding. Indeed, they often used concepts without grasping any meaning, e.g., ‘the salt bridge is used to maintain electroneutrality’. Also, some tended to use algorithms and equations (while neither grasping their basis nor implications) to replace the explanation of a phenomenon, rather than to substantiate it. Their language and reasoning showed a strong tendency to ‘apply’, ‘confirm’, and ‘satisfy’ equations.

We observed quite some use of *hybrid models*, e.g., “the slope is constant and at some point, it starts changing again […] that's where the actual reaction starts happening again”; which denotes an unnoticed mix of explanatory routes. Further, the groundless or wrong *attribution* of effect (e.g., causality, mediation, interaction, contribution) appear to be connected to the rote application of equations, e.g.,

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[8] Alternative research methods could be more sensitive and reveal some measurable growth that escaped from this investigation.

"increasing the concentration of reductor results in a lower voltage *because* the concentration is in the denominator of the Nernst equation".

Instances of *too early labelling* (i.e., too early connection of labels to meaning) were observed a few times. E.g., using the terms 'cathode' and 'anode' without understanding what happens at each electrode, as if the very name would convey some meaning. Instances of *misinterpreted language* were infrequent, though observable, e.g.., 'scanning' was understood as 'monitoring, measuring, reading', while 'scanning' in voltammetry is used to denote the deliberate variation of a potential difference at a constant rate. Such misinterpretation has significant consequences on the students' interpretation of the kind of variables, the objective of the experiment, and their very role as engineering-scientists.

Few instances of *mixed meanings* (i.e., simultaneous use of multiple definitions) were observed. No instances of *misleading analogy* were identified.

3.3 Other qualitative differences in terms of content

We captured (evolving) conceptions of the task, as students acknowledged aspects of the task in conversation with the LAs. On the one hand, the students seemed initially concerned about not grasping what was expected from them and about the complexity of the task; on the other hand, they tended to reduce complexity in some (inappropriate) way.

3.4 Use of conceptual modelling

The B&K method was insufficiently used (either implicitely or explicitly). Basically, we found lack of identification of the phenomenon of interest, and vagueness about the epistemic purpose of the conceptual model. In general, there is lack of prediction or hypothesis. Moreover, variables are often mentioned, but (almost) invariably in terms of their measurability (i.e., at the expense of the distinction between manipulated and controlled variables). These findings are likely to be connected to each other. The students often behaved as passive observers of variables that can only be measured, without acknowledging the possibilities to 'play', intervene, manipulate, so to produce a change that they may wish to predict, test, and describe or explain.

4 DISCUSSION AND CONCLUSIONS

To address RQ1 is to explore how students learn electrochemistry under the intervention as implemented and in terms of indicators of progress in reasoning. Although the implementation of the conceptual modelling approach [7,8] seems not to have reached its full power, the findings are certainly informative. They suggest that students (and instructors) still struggle with shifts from traditional epistemologies, and from traditional learning-and-teaching approaches. On the other hand, students do not necessarily have to comply with the 'levels of complexity' [9] framework, i.e., it is desirable that they reach higher levels regardless of the path they follow. Rather than attempting to force the students into certain steps, instructional designers and educational researchers could analyse the shortcuts students take and plausibly adopt them (i.e., capitalise on them) with appropriate guidance and in a way that is consistent with the overall pedagogical approach. This may contribute to students' embracing complexity and adopting deep learning strategies [3]. Finally, our findings on KRD are line with and add specificity to the existing knowledge [10]. These insights call for micro-interventions aiming to prevent such 'known recurrent difficulties' in learning and teaching from re-occurring. Such micro-interventions might not be easy to realise and should attack the underlying reasons for those difficulties to remain recurrent, despite being well-known.

Addressing RQ2 is to describe in what ways the student learning is embedded in the learning environment. A 'thick description' [4] is available, integrating behavioural aspects of learning (e.g., indicators of progress in reasoning) to contextual conditions of the learning environment (e.g., sequencing of the learning activities). This aims at a generalisation to non-observed cases [13] , so our claims can be extended beyond the empirical context. The analytical description of the context, next to the connections to relevant theoretical frameworks[9], allow us to suggest that our conclusions are tenable and valuable in other engineering-sciences disciplines, as students also struggle with theoretical concepts and with epistemological shifts.

In its turn, RQ3 seeks to evaluate to what extent the intervention has any measurable effect on the learning outcomes and needs to be addressed in a further investigation, as soon as the intervention has been re-implemented (as much as feasible) as designed, or with modifications.

Our findings are informative for revision of the pedagogical intervention and generate some recommendations which can be grouped in three areas. First, about students' conception of the task and believes about their roles: (i) help students to embrace complexity rather than reducing it, (ii) request the thorough use of the B&K method, (iii) distinguish 'manipulated' variables from 'controlled' variables. Second, concerning building on previous for further growing: (i) consider reducing the number of 'different' practicums to allow for a second lab experience around the same topic, (ii) emphasise the connections between 'different' practicums. And third, on collaborative learning: (i) introduce peer review of intermediate/final products, (ii) continue investing in the professionalisation of the LAs.

To conclude, this investigation may be expected to contribute directly to the learning and professional development of those involved, which is consistent with the spirit of action research. The plausible implications on engineering-science educational practice regard new insights and recommendations likely to raise awareness among instructional designers and teachers, thus motivating them to reconsider their own practices, be it in line with an epistemological shift towards scientific reasoning in

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[9] We propose that the frameworks used in this action research project, as well as our operationalisation of such frameworks, are valuable for engineering-science education in general. We refer to frameworks of conceptual modelling, surface/deep approach to learning, levels of complexity, and known recurrent difficulties. Also, we refer to pedagogical ideas about sequencing of activities (e.g., IBL) and a mixed general-infusion approach to instruction and learning (e.g., deliberate/overt, and both general and content-bound).

and for practice. Concurrently, this contribution advances an operationalised framework of levels of complexity for other educational researchers to study learning in engineering-science education.

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