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Learning electrochemistry through scientific inquiry. Conceptual modelling as learning objective and as scaffold

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ABSTRACT

This paper reports on the design of an innovative Electrochemistry course, part of a Chemical Science Engineering programme. Teachers have observed that their students' understanding of electrochemical concepts and phenomena is insufficient to attempt connections to further concepts, and to generate new knowledge in scientific problem-solving. A new course was required aiming to contribute to students' building mastery of concepts and deep insight into phenomena, both in and beyond the learning context. The course was designed tapping on ideas of inquiry-based learning and involving of conceptual modelling as a scaffold to learning. This pedagogical intervention departs from the consideration that conceptual modelling is an essential reasoning ability of (engineering) scientists and, consistently, it constitutes a key learning objective. Concurrent with the implementation of this course, an accompanying empirical investigation was set up to grasp how students learn electrochemistry with this novel pedagogical approach, and whether (and to what extent) there is any observable effect on the learning and transfer of electrochemical concepts. Both the instructional design of the course and the educational research design integrate considerations from Chemical Science, Philosophy of Science in Practice, and Education Sciences. The implications for engineering education and for educational research are discussed.

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Introduction to this paper

Chemical Science Engineering (CSE) graduates are expected to become experts in topics relevant to the future of our society. In particular, Electrochemistry is an important scientific and practical domain within CSE, as it offers a wide range of possibilities to contribute to the development of new (sustainable) processes; examples are water electrolysis to produce hydrogen for its use as a renewable and sustainable fuel, and the development of a battery for more efficient storage of electrical energy (Fuller and Harb 2018). Therefore, teaching electrochemistry in CSE programmes should aim at students' meeting these high expectations.

However, students seem to be more concerned with 'the mathematics of getting a sufficient grade at the end of a module, than with efforts to develop into academically thinking professionals'.¹ Such mindset plausibly represents a contributing factor for a generalised surface approach to learning. Teachers in higher bachelors' and masters' levels have often observed that students cannot rely on sufficient understanding of electrochemical concepts and phenomena. A growing mastery of concepts is necessary

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(Orozco 2022, forthcoming) when new topics are offered, so that students can revisit and connect more familiar electrochemical concepts to more advanced thermodynamical concepts; e.g. connecting 'cell potential' to 'Gibbs free energy' both conceptually and through the use of the Nernst equation (Fuller and Harb 2018). Also, deep insight into electrochemical phenomena is necessary when students are confronted with scientific problem-solving (such as chemical reactor design), where they have to generate new knowledge, e.g. through adaptive transfer (Bransford and Schwartz 1999).

If engineering students are expected to approach their learning differently, they have to be shown how this is possible and be supported in developing advanced thinking skills. In particular, if students are expected to achieve deep insight into electrochemical phenomena and a high level of mastery of electrochemical concepts, both in and beyond the learning context, then a novel instructional design is required that can effectively contribute to reaching such goals. In response to these needs, a team of teachers and educational researchers designed a new course (part of a broader intervention) which taps on ideas of inquiry-based learning (e.g. Pedaste et al. 2015), that approaches the teaching of thinking in an explicit and content-related fashion (Ennis 1989), and that is guided by the use of conceptual modelling as a scaffold to learning.

The broader pedagogical intervention is composed of various elements that are integrated into a mixed general-infusion approach to teaching (Ennis 1989). This intervention departs from the consideration that conceptual modelling is an essential reasoning ability of (engineering) scientists (Boon 2020; Boon and Knuuttila 2009) and, consistently, it constitutes a key learning objective of this course. When used as a scaffold to learning (e.g. Ippolito 2019), conceptual modelling aims to enhance students' understanding of natural phenomena by confronting students with strategies for conducting scientific research.

The implementation of this course is accompanied by empirical educational research aiming to evaluate the effectiveness of this novel approach, i.e. whether (and to what extent) there is any observable effect on both the learning and the transfer of electrochemical concepts. Furthermore, this research addresses a more fundamental question of how students learn electrochemistry during the period of this intervention, i.e. how students' reasoning progresses during the learning process. Both the instructional design of the course and the educational research design integrate considerations from Chemical Science, Philosophy of Science in Practice, and Education Sciences.

This paper is further organised into four sections. The first section regards the relevance of electrochemistry in engineering science education. The second section focuses on the theoretical framework, thus introducing the basis of the ongoing action research project. Subsequently, section three presents the project itself. Finally, the fourth section revisits the connections between our theoretical framework and our action research, next discusses methodological threats and, eventually, proposes plausible implications.

Electrochemistry and engineering science education

Electrochemistry belongs to the broader equilibrium thermodynamics. It is concerned with the chemistry and physics of systems in which chemical reactions can produce an electrical current or, conversely, an external electrical potential is applied to provoke the reaction of species. Not only are electrochemical concepts used to understand naturally occurring phenomena, such as corrosion, but they also have numerous applications, such as electroanalytical techniques, superconductors, electrodeposition, and industrial electrowinning.

In particular, knowledge of electrochemistry is crucial to understand, re-design, or design and develop more sustainable processes and materials for energy conversion and storage; for example: batteries, fuel cells and electrolysis for hydrogen production.

From chemical and electronics manufacturing, to hybrid vehicles, energy storage, and beyond, electrochemical engineering touches many industries—any many lives—every day. As energy conservation becomes of central

importance, so too does the science that helps us reduce consumption, reduce waste, and lessen our impact on the planet. (Fuller and Harb 2018, front)

The preceding quote leaves no doubt on the relevance of electrochemical engineering; from this it follows that engineering science education has an important role to play. We advocate that a conducive approach consists in integrating (or re-integrating) theoretical concepts to empirical work; in order to provide both critical disciplinary knowledge and scientific thinking skills that ultimately find applications in real-world contexts.

Framework

The present theoretical framework is constructed on four main topics: (i) a perspective on learning and transfer of knowledge, (ii) reflective learning, (iii) scientific inquiry as a learning approach, and (iv) conceptual modelling.

Learning and transfer

There are different metaphors for learning that condense distinctive conceptions of learning, and the implications such conceptions have for educational practice (Derry 2017) (e.g. how we approach learning, teaching and assessment). The acquisition and the construction metaphors have first been identified (Tynjälä 2008), while the mastery metaphor has been more recently proposed (Taylor, Noorloos, and Bakker 2017). At this point, a comparative exposition of these metaphors would lead us away from our focus, but we refer the reader to the cited works.

We propose that the mastery metaphor is the most conducive to our action research goals, because it conceives learning predominantly in terms of normative social reasoning activity. According to this perspective, learning is regarded as ‘acquisition of mastery over socio-cognitive capacities, as ratified in (linguistic) practice’ (Taylor, Noorloos, and Bakker 2017, 780). This perspective is useful, furthermore, to propose what it means to ‘understand’ a concept and how such understanding further develops (Orozco 2022, forthcoming). Such view aligns with the well-known emphasis on a deep approach to qualitative learning (Case and Gunstone 2003; Lindblom-Ylänne, Parpala, and Postareff 2019; Marton and Säljö 1976, 1997), as opposed to surface learning.

No less controversial and rich, is the debate on what constitutes ‘the transfer of knowledge’. Indeed, there are several coexisting perspectives on transfer that differ in their assumptions about: what is exactly transferred (Salomon and Perkins 1989), what triggers transfer and how it develops (Lobato 2012; Salomon and Perkins 1989), what distinguishes mere learning from transfer (Salomon and Perkins 1989), what distinguishes mere application from adaptive and generative use of knowledge (Bransford and Schwartz 1999; Eraut 1985), at what point transfer turns overzealous (Schwartz, Chase, and Bransford 2012), and what can be taken to be a misconception in prior knowledge (Lobato 2006; Lobato et al. 2015). The answers we give to these questions have implications on how we teach to transfer (Engle et al. 2012) and assess transfer (Schwartz, Bransford, and Sears 2005), and on our empirical research methods concerning transfer (Lobato 2008).

We use the term ‘transfer of knowledge’ for practical reasons, but we do not subscribe to its connotations, e.g. a reification of knowledge as a good that is carried over from an initial context of learning to a target context of application (Lobato 2006; Perkins and Salomon 2012). Instead, we propose that it is appropriate to conceive transfer as the generalisation of concepts to more encompassing contexts (Engle et al. 2012), which is consistent with a learner-centred perspective and its research methodology (Lobato 2012).

Finally, several authors use the broad idea of ‘making connections’ to point out that much transfer begins during learning, e.g. by creating expectations from the start (Blanchard, Thacker, and Pichai 2013), by deliberately providing forward-reaching cues at any stage (Salomon and Perkins 1989), or by explicitly discussing known and plausible uses of concepts and principles on reflection, thus

preventing mere acquisition of inert knowledge (e.g. Marzano and al 1988). Eventually, this making connections renders knowledge more meaningful for the students (Orozco, Gijbels, and Timmerman 2020).

Reflective learning

The kind of learning we aim for, as described in the previous paragraphs, strongly connects to the idea of 'reflective learning'. The term 'reflective approach' to learning (Lindblom-Ylänne, Parpala, and Postareff 2019) refers to the well-known concept of 'deep approach' to studying (Marton and Säljö 1976, 1997), originally called 'deep processing'. The categories deep and surface are widely accepted to typify qualitative differences in approaches to learning, be it in terms of the referential aspect of students' experiences (i.e. whether the students search for meaning or not), which remains inextricably mixed with the organisational aspect (i.e. whether the informational content is organised in a holistic or an atomistic way) (Marton and Säljö 1997).

Marton and Säljö's (1976) phenomenographic work examined strategies of learning in higher education, as well as the outcomes of such learning. These outcomes were investigated in terms of what is understood and remembered, i.e. with emphasis on what is learned rather than how much. The different levels of outcomes found contain (a) different conceptions of the content of the very task, and (b) correspond to differences in processing.

Our studies have been concerned with meaningful learning in the true sense of this term. The primary aim was to explore qualitative differences in what is learned and to describe the functional differences in the process of learning which give rise to the qualitative differences in outcome. [...] The most important conclusion [...] is that learning should be described in terms of its content. A highly significant aspect of learning is, in our opinion, the variation in what is learned, i.e. the diversity of ways in which the same phenomenon, concept or principle is apprehended by different students. By gaining knowledge about how students comprehend, for instance, various scientific principles and ideas, we should obtain information which would undoubtedly prove fruitful for teaching. (Marton and Säljö 1976, 10)

Indeed, it appears crucial to describe the outcome of the learning in terms of the conceptions of the phenomena learned about, which calls for knowing what conceptions of the phenomena (and the concepts included therein) the students already hold, as immediate implication for teaching (Marton and Säljö 1997). Moreover, 'it is exactly in transitions between preconceived ideas of the phenomena and an improved understanding of those phenomena, where the most important form of learning in higher education is to be found' (Marton and Säljö 1997, 57).

Lindblom-Ylänne and colleagues (2019) further examined the nature of the surface approach to learning in higher education and explored explanatory factors for students' use of such approach. The authors suggest that several factors contribute to its use, e.g. extent of organised studying, motivation to study, interest, perception of challenge, and self-efficacy beliefs. Furthermore, it is suggested that both students' unreflective studying and their strong perception of a fragmented knowledge base are at the core of the surface approach (Lindblom-Ylänne, Parpala, and Postareff 2019). It is important to consider the implications of these conclusions in (our) educational practice and action research. In the discussion section, we also connect with other researchers' work on the factors for students' approach, and the strategies to enhance mastery and deep learning in the context of Electrochemistry (De Jong and Treagust 2002; Rahayu, Treagust, and Chandrasegaran 2021; Schmidt, Marohn, and Harrison 2007; Treagust, Mthembu, and Chandrasegaran 2014).

Scientific inquiry as learning approach and object of learning

Inquiry-based learning

Inquiry-based learning (IBL) is a methodology that aims to enhance learning through a knowledge construction process (Santana-Vega, Suarez-Perdomo, and Feliciano-Garcia 2020). It is widely accepted that inquiry experiences can provide valuable opportunities for students to develop a

higher level of understanding of both science content and scientific practices (Edelson, Gordin, and Pea 1999).

IBL is usually organised into inquiry phases that together form an inquiry cycle, although many variations on this cycle are found (Pedaste et al. 2015). In most cases, five phases can be distinguished, i.e.: (i) orientation, (ii) conceptualisation, (iii) investigation, (iv) conclusion and (v) discussion. The latter includes communication and reflection, and is expected to be present at every point during IBL (Pedaste et al. 2015).

Prior research has consistently shown that IBL can be more effective than instructional approaches that tend to be more expository (i.e. more instructor-centred than student-centred), as long as students are supported adequately (Lazonder and Harmsen 2016). Yet it is not straightforward to state what type of guidance is adequate, and for whom. Meta-analyses have shown that the type of guidance does not moderate the overall effects, but the effects on particular learning outcomes present considerable variation (Lazonder and Harmsen 2016).

Compared to more traditional learning models, IBL presents both advantages and disadvantages that should not be overlooked, if we aim to meet teachers and students' expectations (Khalaf and Zin 2018). More than just focusing on students' performance and learning outcomes, Khalaf and Zin (2018) emphasise that various pedagogical aspects should be considered concurrently. The implementation of IBL presents significant challenges (Edelson, Gordin, and Pea 1999): (a) higher level of student motivation required, (b) accessibility of investigation techniques, (c) opportunities to develop and readily engage scientific understanding, (d) planning and organisation of activities and resources, (e) practical constraints of the learning environment. Strategies proposed in the literature for addressing such challenges, still need to be adapted to the particular learning environment.

Madhuri and colleagues (2012) provide an example of an inquiry-based approach in engineering education. They redesigned a chemistry course to focus on: the students' ability to execute an experiment, design new experiments, and connect the practical utility of the course module to real-life problems. This intervention attempts to overcome the problem that 'students can be successful in their laboratory class even with little understanding of what they are actually doing' (Madhuri, Kantamreddi, and Prakash Goteti 2012, 118).

All in all, considering the aforementioned issues during the instructional design and the implementation, IBL can offer a space for the creation of knowledge that is stimulated by the inquiry process (Santana-Vega, Suarez-Perdomo, and Feliciano-Garcia 2020), thus favouring meaningful learning.

Learning through and about scientific inquiry

Concurrently to its use as a learning approach, the scientific inquiry needs to be the object of learning as well. Too often, books and lectures present scientific-technological models to students, that have been deprived of inside knowledge of the process of construction of such models (Knuuttila and Boon 2011). By attending to the creative process of knowledge generation, students will develop an insight into the epistemology of science in practice. They will make sense of what they see or measure during their empirical work in the lab (and even what they cannot see), thus getting the feeling that they really grasp what is going on. Students will grow intellectually through the construction and reconstruction of conceptual models. Indeed, modelling has been recognised as a core practice in science and as a central part of scientific literacy (Schwarz et al. 2009); in particular, scientific modelling of technological systems is central to the engineering sciences (Boon 2020).

IBL plays a role in such intellectual growth, as it helps to convey the idea that theory is not necessarily a 'foundation' that has to come first per se. In this way, it becomes possible to question assumptions underlying expressions such as 'putting theory into practice', 'applying theory' or 'confirming theory in the lab' (Orozco, Gijbels, and Timmerman 2020).

IBL then allows us to modify the traditional sequence of learning activities, such that the students' inquiry and discovery come first, and it is followed by integration to conceptual knowledge (Orozco, Gijbels, and Timmerman 2019). The conceptual modelling approach (Boon and Knuuttila 2009; Knuuttila and Boon 2011) guides the students in performing such integration. Yet it remains of utmost importance to develop a thoughtful learning progression for scientific modelling, if we aim to make modelling accessible and meaningful for the students (Schwarz et al. 2009).

Schwarz and colleagues (2009) propose a learning progression for scientific modelling based on the interaction of elements of practice and metamodeling knowledge. The elements of practice refer to activities such as constructing, using, evaluating, and revising; while the metamodeling knowledge (which guides and motivates practice) includes an understanding of the nature and purposes of models, along with consideration of criteria for evaluating and revising the models. Within this framework, various levels of progress can be identified (Schwarz et al. 2009): four levels along the generative dimension (i.e. scientific models as tools for predicting and explaining), and four levels along the understanding dimension (acknowledging that models change as understanding improves). There is evidence to suggest that sufficient support to students is a condition for them to make progress: '[...] we found that with sufficient support, students were able to revise their models and explain how their models were improved from their earlier versions, referring to increasingly sophisticated criteria' (Schwarz et al. 2009, 651)

Conceptual models: their elements and construction

A conceptual model can be considered an 'epistemic tool', i.e. a tool for thinking that allows us to understand and to generate new knowledge (Boon and Knuuttila 2009; Knuuttila and Boon 2011). The action of modelling, in its turn, involves a 'way of reasoning', i.e. an important academic skill that we wish to promote as a learning objective in engineering science education.

The methodology proposed for constructing scientific models of phenomena (either physical or physical-technological) is consistent with the hypothetical-deductive methodology of inquiry (Boon 2020). Such methodology encompasses both the modelling of physical-technological phenomena in a specific context, and the modelling of technological artefacts that produce specific phenomena.

There are several aspects that a scientific model of a phenomenon needs to include, such as: an identification of the problem context and the phenomena of interest, an inventory of the relevant properties and variables involved, a distinction between measurable and not measurable variables (with current technology), the associated instruments of measure (if any), and the theoretical and empirical connections between the various elements of the model (either known or hypothesised). The justification of the model is partially given by how it is built, i.e. by the coherent integration of the elements into a whole (Boon and Knuuttila 2009; Knuuttila and Boon 2011).

Action research in engineering science education

This section first introduces action research (its concept, principles, and examples of use in engineering education). Next, we describe the main aspects of the context (and its disciplinary content) in which the present educational research is embedded. Further, we enter the elaboration of the proper action research; here, the 'action part' focuses on the instructional design of the pedagogical intervention, while the 'research part' focuses on the design of the accompanying phenomenological research.

Introduction to action research

Action research is 'a powerful tool for change and improvement at the local level' (Cohen, Manion, and Morrison 2011, 344). In education, participatory action research is a way in which teachers research their own courses, be it individually or collaboratively with other teachers and/or researchers. Although there are several schools of action research, they have in common their desire for the

Table 1. Key principles of action research present in the current study.

Action research principles	Current study
Improving education by changing it	Intervention design and implementation
Participatory: improvement of the own practices in the first place	Teachers as initiators and further involved in various aspects of the action research
Self-reflective spiral: planning, acting, observing, reflecting	Built in the research design and assisted by the researchers
Collaboration	Teachers-researcher close collaboration
Theorising, being inquisitive, coming to understand relationships	Plausible explanations will be discussed after evidence-based conclusions are drawn
Own practices put to the test, gathering compelling evidence	Built in the research design and assisted by the researchers
Keeping records, also collecting, and analysing own judgements, reactions, and impressions	Keeping a personal journal is recommended to the teachers involved
Reasoned justification: a developed, tested and critically examined rationale for what we are doing	Evidential trail constructed throughout the project, based on the gathered evidence and critical reflection

advancement of educational practice, 'based on a rigorous evidential trail of data and research' (Cohen, Manion, and Morrison 2011, 344).

Action research bridges the gap between educational research and practice by combining diagnosis, action and reflection, and by focussing on issues that have been identified by the very practitioners (Cohen, Manion, and Morrison 2011). In our project, teaching practitioners and educational researchers work alongside in the area of teaching methods (i.e. in order to introduce a novel course, in which traditional teaching methods are replaced by a scaffolded discovery method). Table 1 highlights some key principles of action research (Kemmis and McTaggart 1992) and indicates how such principles are present in our particular study, i.e. to design, implement, execute, monitor and understand the effects of the pedagogical intervention.

There are many published examples of action research in education, although only few of them in the context of engineering education. One example pertains to the design and use of learning mini-projects in a chemistry laboratory for engineering, in order to make the learning activities in the classroom resemble the activities in real companies (Cancela et al. 2016). Another example concerns the development of chemical engineering course methods, using systematically extracted data from student feedback and teacher reflection over a period of several years, and with the aim of improving the quality of teaching (Virkki-Hatakka, Tuunila, and Nurkka 2013).

The context of this study

The present action research is embedded in a bachelor's programme that focuses on the technological application of chemistry. Students will expectedly become professionals able to contribute to improving and developing processes and materials, while using disciplinary knowledge (along with scientific thinking skills) as their starting point.

This three-year programme is organised into 12 modules that combine a broad range of compulsory and elective subjects. These include not only the more foundational topics (such as chemistry, material science, thermodynamics, transport phenomena and quantum chemistry), but also the more technological topics (such as industrial processes and process equipment design). Strategies such as project-based assignments and the bachelor thesis aim at the integration of the various subjects (either during the initial learning or in retrospect). The main context of our study is in Module 4 (and in particular the Electrochemistry course), hosting both the intervention and most educational research activities. Also, Module 5 (the courses in Kinetics and in Industrial Chemical Processes) will host research activities related to the question on transfer of knowledge.

The content in this study

Part of Module 4 of the bachelor's programme is concerned with equilibrium thermodynamics. This area is interested in, e.g. (a) describing and quantifying changes in the state of a substance as a result

of phase transitions, mixing, or chemical reactions, (b) predicting whether a process will run spontaneously under certain conditions, and (c) determining the composition and state conditions of a mixture in equilibrium. This knowledge is the foundation for the design of nearly all industrial processes, i.e. its technology, operation, and products.

Next to the lectures on electrochemistry theory, a lab course is designed and conducted. Five practicums are planned, to be performed by small groups of students (combining individual and group tasks); these are: (1) potentiometric meter, (2) electrochemical cell, (3) solubility, (4) acid–base potentiometric titration, (5) voltammetry. In the present study, we are particularly interested in the second and fifth practicums. We selected the second topic, electrochemical cell, for being both particularly challenging for the students (in terms of difficulty) and particularly relevant (in terms of eventual applications, as explained before). We selected the fifth topic, voltammetry, because it somehow integrates and extends all other topics.

Instructional design of the intervention

Mixed infusion-general teaching of thinking

We propose that much of what is known about critical thinking can be used to understand, promote, and evaluate scientific thinking as well. Just as critical thinking has a heavily loaded logical dimension, next to its criterial and pragmatic dimensions (Ennis 1962), scientific-technological conceptual modelling can be regarded as a way of reasoning (Boon 2020). In this sense, conclusions about the subject specificity of critical thinking and their pedagogical implications (Ennis 1989) can be extended to the teaching of scientific reasoning.

In line with Ennis' views (1989), the most appropriate approach to teaching scientific reasoning appears to be a mix of a 'general approach' and an 'infusion approach'. This means teaching principles of conceptual modelling both in a context-free fashion (the general approach) and connected to the particular domain of interest, in this case electrochemistry (the infusion approach). A further characteristic of the infusion approach is that it offers the principles of conceptual modelling in an explicit way (thus providing a vocabulary, and the tools for communication and reflection). We add that a mere combination of approaches will not be conducive, and that the two approaches need to be integrated.

Conceptual modelling as a learning objective and as a scaffold for learning and transfer

In this project, the conceptual modelling skill is regarded as a learning objective, while the modelling activity plays the role of a scaffold in engineering science education. As explained before, the action of modelling involves a scientific way of reasoning and, therefore, it represents a desired academic skill and an intended learning objective of the proposed pedagogical intervention.

Furthermore, the process of modelling uses the B&K method (Boon and Knuuttila 2009; Knuuttila and Boon 2011) as a scaffold for the learning and persistent use of conceptual modelling. In educational sciences, the term 'scaffold' refers to an educational or instructional strategy (or even an artefact) intended to promote a desirable outcome (e.g. the effective development of a group of skills). Originally, a 'scaffold' is deliberately temporary and meant to fade over time (Newstetter 2005; van Merriënboer 2013). However, our use of 'scaffold' particularly refers to a 'cognitive scaffold' (Ippolito 2019) and presupposes its persistence over time. Examples of such a cognitive scaffold are 'reflection prompts' (Davis and Linn 2000), intended to assist students in becoming, and remaining, autonomous integrators of their knowledge. We take a scaffold to be more than just a procedure that is demonstrated by an instructor and that students need to internalise, so that it becomes automated or and the instructor's support becomes superfluous. The persistent and effective use of the scaffold (either deliberately or unconsciously) is an indicator of the attained level of cognitive skill development.

In particular, the B&K method (Boon and Knuuttila 2009; Knuuttila and Boon 2011) is a scaffold that guides reasoning in terms of the aspects that need to be collected and related in the modelling

processes; this requires critical thinking of what is relevant (or not) for understanding the modelled phenomenon, in a specific problem-context and for an intended epistemic purpose.

The proper intervention

The proper intervention consists mainly of a new electrochemistry course (focused on the lab practicums and tapping on IBL methodology). This course is supported by a preliminary lecture on conceptual modelling for the students, and a workshop on conceptual modelling for learning assistants (and interested teachers). Two theoretical lectures per lab practicum complete the overall intervention, i.e. an introductory lecture and a recapitulation lecture. Table 2 summarises the overall sequence.

The students are expected to achieve a high level of understanding of electrochemistry, through scientific thinking and through the integration of empirical observations and theoretical knowledge. The assessment of students' learning (process and product aspects) has at least three purposes, i.e. formative, evaluative, collecting evidence. Various assessment instruments will be involved in our investigation, i.e. lab journals (including reflection reports), intermediate and final practicum reports, informal quizzes, and a final exam. These documents will be appraised in the light of the learning objectives, the levels of progress for scientific modelling (Schwarz et al. 2009), and triangulated with accounts of the subjects' experiences.

The new electrochemistry course: focus on the practicums. The electrochemistry lab course is designed according to IBL principles. It is centred on the use of conceptual modelling to guide the scientific reasoning (including the integration of the students' empirical observations to the theory of electrochemistry) and is assisted by the B&K method as a scaffold for developing the modelling skills. There are several practicums to be performed, each with specific aims and learning objectives, as explained before.

The five practicums composing this course (each with specific aims and learning objectives) are conducted by groups of students (16 groups, 3 students each), while alternating individual and collaborative tasks. Each practicum involves understanding a particular electrochemical phenomenon (or even tackling a particular scientific electrochemical problem). The learning process is facilitated by learning assistants (LA), whose main task is to guide the students' reasoning in the process of modelling at several stages before and after the actual empirical work. Also, both the students' learning process and the assistants' task are facilitated by a semi structured lab journal. This lab journal, furthermore, constitutes an important instrument for the assessment of the learning process, while it

Table 2. Overall sequence of the intervention.

ID	Section	Comment
	Introduction: Overall aims & learning objectives	For students
	Workshop on conceptual modelling	For learning assistants (and interested teachers)
	Interactive lecture: Introduction to conceptual modelling	For students
	Interactive lecture: Activating theoretical concepts	For students, before each practicum
1	Practicum: Potentiometric meter	Sequence shown in Table 3
2	Practicum: Electrochemical cell	Sequence shown in Table 3
	Intervision meeting	For learning assistants (and interested teachers)
3	Practicum: Solubility	Sequence shown in Table 3
4	Practicum: Acid-base reactions & electricity	Sequence shown in Table 3
	Feedback on groups' conceptual models on submission of lab reports	For students, after each practicum
	Interactive lecture: Anchoring connections & drawing new ones	For students, after each practicum
5	Practicum: Voltammetry	Sequence shown in Table 3
	Feedback on groups' conceptual model on submission of the final lab report	For students, formative closure
	Exam & Composition of process evaluation	Summative assessment

Table 3. Sequence of learning activities of per practicum (summary).

ID	Activity	By whom
a	Brief theoretical introduction	Lecturer
b	Preparing the practicum + C.Model ₀	Students groups
c	Meeting the LA before the practicum	Students groups + LA
d	Conducting the practicum	Individual students
e	Processing and interpreting the data + C.Model ₁	Students groups
f	Meeting the LA	Students groups + LA
g	Short recap of previous week	Lecturer
h	Theoretical self-instruction	Students (individ. or in group)
i	Reporting + C.Model ₂	Students groups
j	Feedback on reports & C.Model ₂ to all S	Practicum teacher

Note: C.Model_i denotes the various versions of the conceptual model.

will also be used as a key data collection instrument for our educational research. Table 3 presents the sequence of learning activities per practicum.

For the present study, we selected the second and fifth practicums for being particularly challenging and integrative (thus providing richer educational research data), while the instructions and approach is nearly the same for all practicums. The second practicum concerns an electrochemical cell; the aim is to determine the electromotive force (EMF) and evaluate whether (and if so, how) cation concentration affects EMF after electrochemical cell assembly. The learning purpose is to build knowledge on electrochemical cell assembly and determine the different phenomena occurring in the cell. After this practicum, the student should explain the working principle of an electrochemical cell (in particular, the relationship between a chemical reaction and electricity) by integrating the learning from their lab experience (i.e. including the analysis of the empirical findings) to (prior) conceptual knowledge on electrochemical electrodes, electrochemical reactions (e.g. species, stoichiometry, equilibrium, reversibility), cell potentials, EMF, and ion diffusion.

Further, we focus on the fifth and last practicum, which has both a formative function (i.e. to integrate and extend the learning from the previous practicums) and an evaluative function (i.e. to assess the achievement of the learning objectives by the student groups). In other terms, this final project aims to challenge the students and use conceptual modelling skills in the project assignment. Additional concepts will be used, such as cyclic voltammetry, to generate insights into the different identified phenomena. After the practicum, the student should know how to integrate the concepts from previous experiments with the voltammetry method.

Lecture on electrochemistry. The students are assumed to have some prior knowledge, such as: fundamentals of chemistry and of thermodynamics. Learning objectives for the integrated course have been formulated as a guide for learning, teaching and assessment.

Before each practicum, an introductory lecture will present the main aspects of the particular topic (Fuller and Harb 2018), without disclosing what the students are supposed to discover by themselves, in line with the principles of IBL (Pedaste et al. 2015) and the learning by scientific discovery (Schwarz et al. 2009).

After each practicum's sequence of activities, a recapitulation lecture will focus on anchoring connections (e.g. between empirical observations and theoretical concepts) made by the students groups during the modelling (Knuutila and Boon 2011; Schwarz et al. 2009). Also, new connections to further applications may be discussed with a view on transfer of meaningful knowledge (Marzano and al 1988; Orozco, Gijbels, and Timmerman 2020).

Lecture on conceptual modelling. The students are expected to have preconceptions about scientific-technological knowledge (along with its generation, validation, and stability) that may not always be conducive to developing academic thinking. Learning objectives for this part of the intervention have been formulated.

This lecture first aims to create awareness about conducive and non-conductive epistemological preconceptions, to then introduce the principles of conceptual modelling (Boon and Knuuttila 2009; Knuuttila and Boon 2011). The lecture is accompanied by a handout for the students' reference.

Providing this lecture on conceptual modelling to students in quite general terms (thus not centred on any particular subject matter) responds to a 'general approach' to teaching scientific reasoning (Ennis 1989). It is not expected that the students will master the modelling skills just after this lecture. Rather, this lecture smoothly integrates with the practicums that use the conceptual modelling method and the B&K scaffold (Boon and Knuuttila 2009; Knuuttila and Boon 2011) in relation to electrochemical concepts and phenomena. These practicums respond to the 'infusion approach' to teaching reasoning (Ennis 1989). The overall approach is an example of a thoroughly integrated mixed approach to teaching.

Training the learning assistants. A two-session workshop is given to the learning assistants for them to start becoming acquainted with the conceptual modelling method. Furthermore, the LAs need to understand what is expected from them at the time of assisting the students groups. Therefore, the workshop first introduces the overall idea and principles, and continues with a more detailed discussion of handouts and manuals that have been written for this course. A third session with the LAs (an 'intervision' meeting) takes place later during the semester, to collect their experiences with the students, to discuss any issues and to steer the intervention if necessary.

The LAs are advanced students in chemical engineering who are particularly interested in the topic of conceptual modelling, and in guiding students in their learning process. These LAs have already received training to assist students in higher education (e.g. introduction to learning and motivation theories, giving qualitative feedback, and dealing with conflicts). Their participation in the present action research project further contributes to their professional development.

Phenomenological research design

The selected research methodology is phenomenological, because we are interested in the subjects' experiences as much as in accurate records of their performances. This is in line with our frameworks about learning (Derry 2017; Taylor, Noorloos, and Bakker 2017) and transfer (Engle et al. 2012; Lobato 2012), as elaborated in a previous section, and in line with the spirit of action research about 'what counts as evidence' (Kemmis and McTaggart 1992). In seeking methodological consistency (Cohen, Manion, and Morrison 2011), we choose to use qualitative methods (strategies, techniques and instruments) of data collection and analysis, that allow us to describe the phenomenon of learning, focussing on the students, learning assistants and teachers' experiences.

The project has three educational research purposes, i.e. to explore, to describe, and to evaluate. As shown in Tables 4–6, each research purpose is translated into a distinctive research question, has its own focus and approach, and makes a different contribution to the overall project. The purposes and research questions are to explore (RQ1) how students learn electrochemistry under the proposed intervention, 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 effect on the learning outcomes.

Explore

Exploring could be seen to extend beyond the scope of the action research approach (if defined narrowly), as it responds to a more fundamental interest to understand the progress of learning. Research question 1 reads: **How do students learn electrochemistry under the proposed intervention?** The research activities will seek to elicit and observe the students' activity and progress in various situations. Table 4 summarises these research activities, including the strategies for data collection and analysis.

Table 4. Research design seeking exploration.

Research question I	How do students learn electrochemistry under the proposed intervention?	
Focus	Elicit the students' reasoning and hands-on activity, during lab practicums	Observe behaviour and conduct recall interviews Content analysis (rather than motor skills) in terms of conceptual modelling learning objectives
	Elicit students' progress in reasoning, during the construction of conceptual models	Collect lab journals and practicum reports (including students' reflections) Content analysis (rather than writing and presentational skills) in terms of conceptual modelling learning objectives
	Elicit students' reasoning and discursive activity, during discussions with their learning assistants	Observe preparatory and feedback meetings Content analysis (rather than conversational) in terms of conceptual modelling learning objectives
Contribution	The answer will provide fundamental understanding on the interaction of the intervention with the process of learning.	

Describe

The description intends to assist further generalisation of the research findings, in terms of external validity (Mortelmans 2020). Research question II reads: **In what ways is student learning embedded in the learning environment?** Responding to this question involves a narrative that integrates various pieces, as shown in Table 5.

Table 5. Research design seeking description.

Research question II	In what ways is student learning embedded in the learning environment?	
Focus	Build on the findings related to RQ1 and RQ3: behavioural aspects of learning	Collect indicators of progress in reasoning Comparative analysis
	Relate behavioural aspects of learning to assessment results	Collect process and product evaluation by learning assistants and teachers Comparative analysis, including all learning objectives
	Provide a 'thick description' of the contextual conditions	Synthesise in writing Highlight key elements as tools for generalisation
Contribution	The answer will contextualise the findings and provide tools for generalisation.	

Evaluate

The purpose of evaluating resonates more clearly with the spirit of evidence-based justification, that characterises action research. Here we aim to find out whether and to what extent the new course has any effect on the students' learning and transfer of knowledge. Research question III reads: **To what extent does the intervention have any effect on the learning outcomes?** This question is broken down into (IIIa) near-reaching and far-reaching learning outcomes in Module 4, and (IIIb) in terms of mastery of concepts and the transfer of knowledge to scientific-problem solving situations in Module 5. Such distinction is also shown in Table 6, along with the corresponding data collection and analysis strategies.

Discussion and conclusion

The primary purpose of the present action research project is to enhance students' deep understanding of electrochemical phenomena, with a view on scientific problem-solving within and beyond the initial learning context. This goes hand in hand with the broader learning objective of conceptual modelling to develop into academically thinking professionals. The further goal is to introduce an evidence-based and innovative pedagogical approach that can be rolled out to other learning programmes in engineering science education.

Table 6. Research design seeking evaluation.

Research question III	To what extent does the intervention have any effect on the learning outcomes?	
IIIa	To what extent does the intervention have any effect on the near-reaching and far-reaching learning outcomes?	
Focus	Near-reaching outcomes: reproducing, solving well-structured problems Far-reaching outcomes: inferring, solving ill-structured problems	<ul style="list-style-type: none"> • Collect teachers' perceptions in M4 • Collect last and this years' exams (evaluate the feasibility of comparison) • Analyse the exams comparatively (between cohorts), using the learning objectives as criteria • Triangulate in the light of teachers' perceptions
IIIb	To what extent does the intervention have any effect on mastery of concepts and on the transfer of knowledge to scientific-problem solving?	
Focus	Mastery of concepts in terms of connections to new and/or more encompassing concepts (e.g., inferential connection of 'cell potential' to 'Gibbs free energy') Mastery of concepts in terms of their use in generative/scientific problem-solving	<ul style="list-style-type: none"> • Collect teachers' perceptions in M5 • Follow-up students from M4 to M5: collect exams, quizzes, reports • Analyse the documents comparatively (within the same cohort)
Contribution	The answer will constitute evidence of the effectiveness of the intervention (to the extent that observed differences can be attributed to the intervention, e.g., by means of triangulation)	

We constructed a theoretical framework in which we, firstly, acknowledged our perspectives on learning (i.e. the mastery metaphor) and transfer (i.e. adaptive, learner-centred generalisation). These perspectives have implications for educational practice and research. Secondly, we elaborated on selected teaching approaches (e.g. inquiry-based learning, mixed general-infusion intervention) and provided rationales for our choices. Finally, we focused on conceptual models and on the modelling activity for their key role in the development of academic thinking skills and the deep learning of domain knowledge.

Furthermore, we presented the concept of action research (its meaning and its relevance) while explaining how the action research method is embedded in our context of study, its content, and the empirical setting.

Consistent with our theoretical framework, we advanced an integrated pedagogical intervention that is being implemented in the second bachelor year of a chemical science engineering programme. The main elements of the overall intervention were described, including: the sequencing of theoretical lectures, general teaching of conceptual modelling, and lab practicums scaffolded by conceptual modelling strategies. Importantly, the elements of our intervention are in line with new developments in electrochemistry education to promote a mastery and deep learning approach to learning, e.g.: (i) addressing students' alternative concepts and predictions by making them explicit in group discussions (Schmidt, Marohn, and Harrison 2007; Treagust, Mthembu, and Chandrasegaran 2014), (ii) designing a sequencing by which ambiguous terms are avoided or delayed to prevent misleading mismatches between correct terms and alternative interpretations or meanings (Schmidt, Marohn, and Harrison 2007), (iii) introducing more appropriate experiments that, rather than starting with an experiment that is overwhelming for the students, start with a very simple experiment that allows clarify some basic features of cells, along with the corresponding concepts (De Jong and Treagust 2002). Although these interventions are proposed on the basis of empirical studies, De Jong and Treagust (2002) call for further research to evaluate the 'teachability and learnability' of such new approaches; moreover, the successful implementation of such approaches requires teachers who are both willing and capable to do so; recommendations for teachers professionalisation in this respect are also given.

In the same line, we designed an educational piece of research with three purposes, i.e. (I) to explore how students learn electrochemistry under the proposed intervention, (II) to describe in what ways student learning is embedded in the learning environment, and (III) to evaluate the extent to which the pedagogical intervention has any effect on the learning outcomes. Each

purpose has its own focus and approach and makes a different contribution to the overall project. The first purpose could be seen to extend beyond the scope of the action research approach (if defined narrowly), as it responds to a more fundamental interest to understand the progress of learning. In contrast, the last purpose fits more clearly in the spirit of evidence-based justification. In the middle, the second purpose of the description is to assist further generalisation of the overall findings.

Furthermore, we aim to consider existing knowledge in our research field during the analytical phase of our investigation; this, we expect, will provide a broader perspective and more thorough basis to our conclusions and further work. More specifically, we will attend to known recurrent difficulties in learning and teaching electrochemical concepts, which seem to be rooted on, e.g. rote application of electrochemical concepts and algorithms, the use of multiple definitions/meanings although they stem from different contexts (e.g. the phenomenological, the particulate, the measurement/calculation, and the thermodynamic context), the use multiple or of hybrid models, students' wrong interpretations of language, too early connection of labels to meaning, and misleading analogy (De Jong and Treagust 2002; Schmidt, Marohn, and Harrison 2007). Also, we will consider prior knowledge on contributing factors to students' using particular approaches to learning such as organised studying, motivation to study, interest, perception of challenge, self-efficacy beliefs, and perceptions of fragmented knowledge base (Lindblom-Ylänne, Parpala, and Postareff 2019).

Finally, recent empirical work on understanding concepts of electrochemistry resonates with ours in the importance attached to teachers and LAs' continuing professionalisation, given that conceptual understanding often remains underdeveloped even after years of university education (Rahayu, Treagust, and Chandrasegaran 2021); indeed, the instructors should be aware of alternative conceptions held by students to be prepared to deal with these conceptions in their teaching.

Threats

Next to any limitations that may come up in the course of this action research, so far, we have identified two potential methodological issues. The first one, concerns the feasibility of straightforward comparison of existing to new data (e.g. exam questions of different kind over the years); the comparative analysis might require much interpretation (e.g. via constructed units of analysis, rather than using the 'raw data').

The second issue concerns the attribution of the observed effects (e.g. differences in learning outcomes or other performance indicators) to the intervention. We aim to find evidence for the effectiveness of the intervention but need to be cautious when assuming attributability; the affordances of our research methods may not warranty such claims. On consideration of the actual research procedure, an evaluation will be made on whether it is defensible to claim a quasi-experimental design, where the cohort before the intervention (the control group) is compared to the cohort having the intervention (the experimental group). We plan to use other strategies such as data triangulation and deliberate attention to disconfirming evidence.

Implications

This project is expected to contribute directly to the learning and/or professional development of all involved, in particular the students and the learning assistants. Furthermore, we expect that it will have implications on engineering educational practice, given that the conclusion can be informative for further redesign of the intervention and its implementation in the context of study and in other engineering programmes. Also, implications on educational science, as the findings promise to provide fundamental insight into the interaction of the intervention with the process of learning and the development of scientific reasoning. Finally, implications on philosophy of science in

practice, as the empirical evidence may add to existing knowledge on scientific-technological conceptual modelling, in terms of backing and further refinement or extension.

Note

1. This remark was made by the CSE programme director and reflects the perception of the teachers' team. This claim is based on the staff's extensive experience and careful observation of the students' learning and transfer across the various modules. Such observation connects to the distinction between surface-level and deep-level processing (Marton and Säljö 1976) which, roughly, emphasises the quality and the content of what is learned (rather than how much is learned).

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References

- Blanchard, P. N., J. W. Thacker, and A. Pichai. 2013. *Effective Training: Systems, Strategies, and Practices*. Harlow: Pearson Education.
- Boon, M. 2020. "Scientific Methodology in the Engineering Sciences." In *The Routledge Handbook of the Philosophy of Engineering*, 1st ed., edited by D. P. Michelfelder, and N. Doorn, 80–94. New York: Routledge.
- Boon, M., and T. Knuuttila. 2009. "Models as Epistemic Tools in Engineering Sciences: A Pragmatic Approach." In *Philosophy of Technology and Engineering Sciences. Handbook of the Philosophy of Science*. Vol. 9, edited by A. Meijers, 687–720. Amsterdam: Elsevier.

- Bransford, J. D., and D. L. Schwartz. 1999. "Rethinking Transfer: A Simple Proposal with Multiple Implications." *Review of Research in Education* 24: 61–100.
- Cancela, A., R. Maceiras, A. Sánchez, M. Izquierdo, and S. Urréjola. 2016. "Use of Learning Miniprojects in a Chemistry Laboratory for Engineering." *European Journal of Engineering Education* 41 (1): 23–33.
- Case, J. M., and R. F. Gunstone. 2003. "Approaches to Learning in a Second Year Chemical Engineering Course." *International Journal of Science Education* 25 (7): 801–819.
- Cohen, L., L. Manion, and K. R. B. Morrison. 2011. *Research Methods in Education*. 7th ed. New York: Routledge.
- Davis, E. A., and M. C. Linn. 2000. "Scaffolding Students' Knowledge Integration: Prompts for Reflection in KIE." *International Journal of Science Education* 22 (8): 819–837.
- De Jong, O., and D. Treagust. 2002. "The Teaching and Learning of Electrochemistry." In *Chemical Education: Towards Research-Based Practice*, edited by J. K. Gilbert, O. De Jong, R. Justi, D. Treagust, and J. H. Van Driel, 317–337. Dordrecht: Kluwer Academic Publishers.
- Derry, J. 2017. "An Introduction to Inferentialism in Mathematics Education." *Mathematics Education Research Journal* 29 (4): 403–418.
- Edelson, D. C., D. N. Gordin, and R. D. Pea. 1999. "Addressing the Challenges of Inquiry-Based Learning Through Technology and Curriculum Design." *Journal of the Learning Sciences* 8 (3-4): 391–450.
- Engle, R. A., D. P. Lam, X. S. Meyer, and S. E. Nix. 2012. "How Does Expansive Framing Promote Transfer? Several Proposed Explanations and a Research Agenda for Investigating Them." *Educational Psychologist* 47 (3): 215–231.
- Ennis, R. H. 1962. *A Concept of Critical Thinking*: Harvard Educational Review.
- Ennis, R. H. 1989. "Critical Thinking and Subject Specificity: Clarification and Needed Research." *Educational Researcher* 18 (3): 4–10.
- Eraut, M. 1985. "Knowledge Creation and Knowledge use in Professional Contexts." *Studies in Higher Education* 10 (2): 117–133.
- Fuller, T. F., and J. N. Harb. 2018. *Electrochemical engineering*.
- Ippolito, K. O. 2019. "Cognitive Development: The Scaffold for Critical Thought." *Nursing Education Perspectives* 40 (4): 236–237.
- Kemmis, S., and R. McTaggart. 1992. *The Action Research Planner*. Victoria: Deakin University.
- Khalaf, B. K., and Z. B. M. Zin. 2018. "Traditional and Inquiry-Based Learning Pedagogy: A Systematic Critical Review." *International Journal of Instruction* 11 (4): 545–564.
- Knuuttila, T., and M. Boon. 2011. "How do Models Give us Knowledge? The Case of Carnot's Ideal Heat Engine." *European Journal for Philosophy of Science* 1 (3): 309.
- Lazonder, A. W., and R. Harmsen. 2016. "Meta-Analysis of Inquiry-Based Learning: Effects of Guidance." *Review of Educational Research* 86 (3): 681–718.
- Lindblom-Ylänne, S., A. Parpala, and L. Postareff. 2019. "What Constitutes the Surface Approach to Learning in the Light of new Empirical Evidence?" *Studies in Higher Education* 44 (12): 2183–2195.
- Lobato, J. 2006. "Alternative Perspectives on the Transfer of Learning: History, Issues, and Challenges for Future Research." *The Journal of the Learning Sciences* 15 (4): 431–449.
- Lobato, J. 2008. "Research Methods for Alternative Approaches to Transfer: Implications for Design Experiments." In *Handbook of Design Research Methods in Education: Innovations in Science, Technology, Engineering, and Mathematics Learning and Teaching*, 1st ed., edited by A. E. Kelly, R. A. Lesh, and J. Y. Baek, 167–194. London: Routledge.
- Lobato, J. 2012. "The Actor-Oriented Transfer Perspective and Its Contributions to Educational Research and Practice." *Educational Psychologist* 47 (3): 232–247.
- Lobato, J., C. D. Walters, C. Hohensee, J. Gruver, and J. M. Diamond. 2015. "Leveraging Failure in Design Research." *ZDM: Mathematics Education* 47 (6): 963–979.
- Madhuri, G. V., V. S. S. N. Kantamreddi, and L. N. S. Prakash Goteti. 2012. "Promoting Higher Order Thinking Skills Using Inquiry-Based Learning." *European Journal of Engineering Education* 37 (2): 117–123.
- Marton, F., and R. Säljö. 1976. "On Qualitative Differences in Learning I: Outcome and Process." *British Journal of Educational Psychology* 46: 4–11.
- Marton, F., and R. Säljö. 1997. "Approaches to Learning." In *The Experience of Learning: Implications for Teaching and Studying in Higher Education*, 2nd ed., edited by F. Marton, D. Hounsell, and N. Entwistle, 39–58. Edinburgh: Scottish Academic Press.
- Marzano, R. J., and e al. 1988. *Dimensions of Thinking: A Framework for Curriculum and Instruction*. Alexandria: The Association for Supervision and Curriculum Development.
- Mortelmans, D. 2020. *Manual of Qualitative Research Methods*. Leuven: Acco.
- Newstetter, W. C. 2005. "Designing Cognitive Apprenticeships for Biomedical Engineering." *Journal of Engineering Education* 94 (2): 207–213.
- Orozco, M. 2022. Integrative Learning of Theory and Practice. Exploration, Conceptualisation and Description in the Context of Chemical Process Technology.
- Orozco, M., D. Gijbels, and C. Timmerman. 2019. "Empirical Conceptualisation of Integrative Learning. A Focus on Theory-Practice Integration in Technical Vocational Education and Training." *Vocations and Learning* 12 (3): 405–424.

- Orozco, M., D. Gijbels, and C. Timmerman. 2020. "Conceiving the Relationship Between Theory and Practice in T-VET. An in-Depth Study on key Actors' Epistemological Perspectives." *Journal of Vocational Education and Training* 73 (3): 392–412.
- Pedaste, M., M. Mäeots, L. A. Siiman, T. de Jong, S. A. N. van Riesen, E. T. Kamp, C. C. Manoli, Z. C. Zacharia, and E. Tsourlidaki. 2015. "Phases of Inquiry-Based Learning: Definitions and the Inquiry Cycle." *Educational Research Review* 14: 47–61.
- Perkins, D. N., and G. Salomon. 2012. "Knowledge to Go: A Motivational and Dispositional View of Transfer." *Educational Psychologist* 47 (3): 248–258.
- Rahayu, S., D. F. Treagust, and A. L. Chandrasegaran. 2021. "High School and Preservice Chemistry Teacher Education Students' Understanding of Voltaic and Electrolytic Cell Concepts: Evidence of Consistent Learning Difficulties Across Years." *International Journal of Science and Mathematics Education*. doi:10.1007/s10763-021-10226-6.
- Salomon, G., and D. N. Perkins. 1989. "Rocky Roads to Transfer: Rethinking Mechanism of a Neglected Phenomenon." *Educational Psychologist* 24 (2): 113–142.
- Santana-Vega, L. E., A. Suarez-Perdomo, and L. Feliciano-Garcia. 2020. "Inquiry-based Learning in the University Context: A Systematic Review." *Revista Espanola De Pedagogia* 78 (277): 519–537.
- Schmidt, H., A. Marohn, and A. G. Harrison. 2007. "Factors That Prevent Learning in Electrochemistry." *Journal of Research in Science Teaching* 44 (2): 258–283.
- Schwartz, D., J. D. Bransford, and D. Sears. 2005. "Efficiency and Innovation in Transfer." In *Transfer of Learning from a Modern Multidisciplinary Perspective*, edited by J. P. Mestre, 1–52. IAP: Greenwich, CT.
- Schwartz, D. L., C. C. Chase, and J. D. Bransford. 2012. "Resisting Overzealous Transfer: Coordinating Previously Successful Routines with Needs for New Learning." *Educational Psychologist* 47 (3): 204–214.
- Schwarz, C. V., B. J. Reiser, E. A. Davis, L. Kenyon, A. Achér, D. Fortus, Y. Shwartz, B. Hug, and J. Krajcik. 2009. "Developing a Learning Progression for Scientific Modeling: Making Scientific Modeling Accessible and Meaningful for Learners." *TEA Journal of Research in Science Teaching* 46 (6): 632–654.
- Taylor, S. D., R. Noorloos, and A. Bakker. 2017. "Mastering as an Inferentialist Alternative to the Acquisition and Participation Metaphors for Learning." *Journal of Philosophy of Education* 51 (4): 769–784.
- Treagust, D. F., Z. Mthembu, and A. L. Chandrasegaran. 2014. "Evaluation of the Predict-Observe-Explain Instructional Strategy to Enhance Students' Understanding of Redox Reactions." In *Learning with Understanding in the Chemistry Classroom*, edited by I. Devetak, and S. A. Glazar, 265–286. Dordrecht: Springer Netherlands.
- Tynjälä, P. 2008. "Perspectives Into Learning at the Workplace." *Educational Research Review* 3 (2): 130–154.
- van Merriënboer, J. J. G. 2013. "Perspectives on Problem Solving and Instruction." *Computers & Education* 64: 153–160.
- Virkki-Hatakka, T., R. Tuunila, and N. Nurkka. 2013. "Development of Chemical Engineering Course Methods Using Action Research: Case Study." *European Journal of Engineering Education* 38 (5): 469–484.