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Mapping preservice chemistry teachers' group cognitive structures of electrochemistry and comparison with their understandings of electrochemistry concepts

Canan Nakiboğlu *[a] and Nuri Nakiboğlu [b]

Investigating the relationship between conceptual understanding, as measured by an achievement test on a chemistry topic, and cognitive structure, mapped using a technique that illustrates associations between concepts in learners' minds, can provide valuable insights into both the effectiveness of different assessment methods and the differences they reveal. The objectives of this study are threefold: (1) to determine preservice chemistry teachers' conceptual understanding of electrochemistry, (2) to map their cognitive structures related to electrochemistry concepts, and (3) to investigate whether a relationship exists between their conceptual understanding of electrochemistry and their cognitive structures. A total of 80 preservice chemistry teachers (57 females and 23 males) participated in the study. Data were collected using two instruments: the Word Association Test and the Electrochemistry Concept Test. The Word Association Test included ten stimulus concepts: electrolyte, anode, cathode, electrode, reduction, oxidation, salt bridge, electrolysis, conductivity, and electrochemical cell. The Electrochemistry Concept Test consisted of 18 multiple-choice questions, categorized into five distinct sections. Findings from the Electrochemistry Concept Test revealed that preservice chemistry teachers had an average performance of approximately 40%, indicating inconsistencies in their understanding across five conceptual categories. When compared with data from the Word Association Test, students with lower conceptual performance exhibited weaker, sparser, and more fragmented linkages in their cognitive structures. However, low performance may not stem solely from missing scientific connections In some cases, students may form strong yet scientifically inaccurate associations, reflecting persistent alternative conceptions that interfere with the integration of canonical knowledge. Thus, weak conceptual understanding may result from both missing associations and the presence of coherent but incorrect knowledge structures. These findings underscore the need to interpret cognitive structures not only in terms of connectivity patterns but also concerning the scientific accuracy of those associations.

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Introduction

The primary goal of modern science education is not merely to equip students with content knowledge but also to foster the skills, understanding, and awareness necessary for success in an increasingly complex and rapidly changing world. Given the economic, environmental, and social challenges confronting contemporary societies, science education has become more crucial than ever (Nakiboğlu, 2024). Accordingly, science education in schools aims to cultivate scientific thinking skills, provide students with fundamental technological knowledge, enhance environmental awareness, and enable them to make informed decisions in their daily lives. As a core science, chemistry is vital in achieving these educational objectives. Another key emphasis in today's chemistry education is ensuring that students develop a deep understanding of fundamental concepts directly relevant to daily life rather than being overwhelmed with excessive theoretical knowledge.

One of the principal subjects in chemistry is electrochemistry, which includes concepts related to daily life and is also closely related to energy, one of today's crucial issues. For these reasons, electrochemistry content has become one of the fundamental chemistry topics that should be taught to students in-depth. Electrochemistry has taken its place in the chemistry curriculum of upper secondary schools in almost

[a] *Chemistry Education Division, Necatibey Education Faculty, Balikesir University, Balıkesir, Turkey. E-mail: canan@balikesir.edu.tr, nakiboglu2002@yahoo.com*
[b] *Chemistry Department Science and Art Faculty, Balikesr University, Balıkesir, Turkey*

every country. Electrochemistry concepts, closely related to other fields of science and technology, are frequently encountered due to their widespread use in areas such as battery technology, metal coatings, protective coatings, and processes like electrolysis. While electrochemistry forms the basis of various industrial processes and technologies used in daily life, it also plays an important role in the development and use of environmentally friendly technologies. Therefore, teaching the fundamental principles of electrochemistry to upper secondary school students provides them with information about environmentally friendly solutions and raises awareness about sustainability. Conversely, research examining students' understanding of electrochemistry across different educational levels and countries has identified numerous challenges and alternative conceptions related to the topic (Barral *et al.*, 1992; Garnett and Treagust, 1992a, b; Ogude and Bradley, 1994; Sanger and Greenbowe, 1997a; Supasorn, 2015; Siswaningsih and Muchtar, 2017; Loh and Subramaniam, 2018a, b; Amponsah, 2020; Basuki, 2020; Nakiboğlu and Nakiboğlu, 2022; Rahayu *et al.*, 2022; Nakiboğlu *et al.*, 2024). These studies have sought to identify students' alternative conceptions in electrochemistry and to explore the underlying causes of these alternative conceptions. A review of the literature indicates that such investigations are typically conducted through interviews and conceptual achievement tests. When administered before and after instruction, these tools provide valuable insights into the effectiveness of teaching interventions and students' conceptual development. However, it is equally important to understand how newly acquired knowledge is integrated into students' existing cognitive structures. This requires an examination not only of the accuracy of students' knowledge but also of how concepts are mentally organized and interconnected. Conceptual achievement tests, particularly those in multiple-choice formats, offer limited insight into the structure of students' conceptual knowledge. As Tsai and Huang (2002) emphasize, alternative techniques are required to more accurately map students' cognitive structures. Utilizing instruments that reveal cognitive structures enables researchers to explore how conceptual relationships are formed and represented in students' minds. An additional consideration is the comparison of data obtained through cognitive structure mapping with data gathered from conceptual tests administered to the same group of students. This comparison is critical, as the two types of assessments involve different question formats and are designed to capture distinct dimensions of understanding. It is important to note that earlier studies have combined different techniques to evaluate participants' cognitive structures—for example, Derman *et al.* (2024) combined the word association test (WAT) and the free writing technique (FWT) in the topic of acids and bases. The novelty of the present study lies in combining WAT and multiple-choice test questions specifically in the field of electrochemistry. While conceptual understanding is most effectively assessed through open-ended questions and, ideally, paired interviews, such approaches are highly time-consuming. Conducting interviews with a large number of students within a limited timeframe is particularly challenging. Conversely, although multiple-choice tests offer practical advantages, they are limited in their ability to measure conceptual understanding, especially due to the influence of guessing. Moreover, they do not reveal the conceptual connections that students have formed in their minds. Cognitive structure mapping helps to address some of these limitations. When used in conjunction with conceptual tests, it can provide more in-depth and complementary insights into students' conceptual understanding, offering valuable information for both researchers and practitioners.

Therefore, the present study's main aim is not only to assess prospective chemistry teachers' (PSCTs) understanding of electrochemistry using the Electrochemistry Concept Test (ECT) but also to investigate the structure of their conceptual knowledge using WAT. In the present study, the use of WAT was complementary to the validated ECT, which directly assesses conceptual understanding and helps identify alternative conceptions. By comparing the ECT results with the cognitive structures revealed by WAT, we aimed to provide a deeper and more nuanced interpretation of the preservice teachers' understanding. This dual-method approach strengthens the study's validity by enabling the cross-validation of findings: while the ECT reveals students' conceptions or alternative conceptions, the WAT shows how that knowledge is mentally organized, linked, or fragmented. By comparing the results obtained from these two complementary tools, this research offers a more integrated view of PSCTs' conceptual understanding. This dual-assessment approach fills a gap in the literature by demonstrating how different instruments can provide converging or diverging evidence about learners' cognitive structures, thereby offering a richer and more reliable basis for evaluating conceptual learning in science education.

Theoretical framework of the study

The theoretical framework of this study is based on educational and cognitive theories that explain students' conceptual understanding, alternative conceptions, cognitive structures, and approaches to discovering these structures. Since the study examined how students' conceptual understanding and cognitive structures are organized and how they are associated by using two different measurement tools (multiple choice test and WAT), the theoretical framework is built on four basic components. These are explained below, respectively.

Conceptual understanding. Conceptual learning refers to the process by which students acquire comprehensive knowledge about a particular subject and structure this knowledge (Vosniadou, 2007), and it is very complex. It can be said that conceptual understanding emerges as an outcome of the conceptual learning process (Duit and Treagust, 2003). One of the most important points in teaching chemistry is to learn the abstract and complex concepts of chemistry meaningfully, in other words, to provide conceptual understanding. So, conceptual understanding refers to students understanding scientific concepts in depth, not superficially (Chiu *et al.*, 2007). Banda and Nzabahimana (2021) also stated that conceptual understanding requires students to synthesize information and knowledge from known schemas and apply this in a new context.

Alternative conceptions. One of the important obstacles to conceptual understanding can be said to be that students have rooted alternative conceptions that contradict scientific understanding. As Chiu *et al.* report, various terms—such as 'misconceptions,' 'alternative conceptions,' 'children's science,' or 'personal models of reality'—have been used in the literature to describe students' conceptions that differ from scientifically accepted concepts. The terms 'misconception' and 'alternative conceptions' are sometimes used interchangeably in the literature (Nakiboğlu, 2006). However, Taber (2000) makes a clear distinction between the two. According to Taber, the term 'misconception' refers to errors that arise due to misunderstandings during instruction, often caused by issues such as unclear explanations, poor communication, or a student's temporary lack of focus. These misconceptions, he argues, can typically be addressed and rectified with minor clarifications or remedial instruction. In contrast, alternative conceptions or alternative frameworks are fundamentally different; they do not stem from mere communication errors and are not easily resolved through straightforward explanations. Research examining how students comprehend electrochemistry concepts indicates that their difficulties in comprehending this topic extend beyond superficial misunderstandings and cannot be resolved with simple corrective feedback (Nakiboğlu *et al.*, 2024). Accordingly, this study adopts the term 'alternative conception' to describe students' ideas that deviate from scientifically accepted explanations, as it better reflects the persistent and complex nature of these conceptual challenges.

Cognitive structures and approaches to discovering these structures. When the explanations of conceptual understanding aforementioned are examined, it is seen that conceptual understanding process is directly related to the meaningful learning (Ausubel, 1968) and the constructing of knowledge in the cognitive structure. In ensuring meaningful learning, the primary focus is on connecting new knowledge to the existing knowledge structure, and at this point, learners' having alternative understandings regarding prior knowledge may constitute an obstacle to meaningful learning. The concept of prior knowledge suggested by Ausubel supports students' meaningful learning in complex subjects such as chemistry (Ausubel, 1968). Ausubel's meaningful learning theory suggests that new information becomes permanent and in-depth learning when it is associated with students' existing cognitive structures (Ausubel, 1968). This approach allows students to take active roles in the learning process and to process information meaningfully instead of just memorizing it. Ausubel's meaningful theory emphasizes students integrating new information with their existing cognitive structures and states that the teacher should take the student's previous knowledge into consideration during this process. Garnett *et al.* (1995) stated that when students' conceptual knowledge and cognitive structures do not support each other, learning can be superficial and temporary. This situation shows the importance of the cognitive structure that exists in the minds of the learners regarding the subject.

Gorodetsky and Hoz (1985) noted that a learner's cognitive structure refers to the organization of stored knowledge in memory and can be modelled as either a hierarchical framework or a semantic network within the student's long-term memory. For this reason, the human mind's memory systems—long-term memory, short-term memory, and working memory—are interconnected and function collaboratively to process, store, and retrieve information, and crucial for understanding students' learning. Norris (2017) stated that short-term memory is a temporary and flexible memory system capable of storing and processing novel and complex information that is not represented in long-term memory. While long-term memory stores permanent information, short-term memory processes transient information and supports the formation of new representations. All incoming information is organized and processed in the working memory by interaction with knowledge in long-term memory. Each memory plays a distinct yet complementary role in cognitive functioning. Long-term memory is the process by which information is encoded or retrieved, mediating conscious or unconscious processing (Slotnick, 2012). Long-term memory is composed of two distinct systems: episodic and semantic memory (Tulving, 1972). Tulving (1972) defined episodic memory as a memory system that enables individuals to consciously recall personal experiences tied to specific temporal and spatial contexts, structured within an autobiographical framework. While episodic memory stores the specific details of past experiences, it interacts with semantic memory in the conceptual interpretation of these experiences. Kumar (2021) described adult semantic memory as a relatively stable system that encompasses knowledge about the world, concepts, and symbols. Preece (1978) highlighted that semantic memory's association with meaning makes it particularly relevant to science teaching, as it facilitates the understanding and applying scientific concepts. Since semantic memory is related to the semantic information, that is, the semantic connection between words, symbols and concepts, it should not be forgotten that the calculated semantic relatedness of two concepts in the semantic memory expresses how similar these two concepts are in the student's long-term memory. It is not an indicator of how the student organizes them based on his/her experiences and scientific knowledge. On the other hand, the hypothetical structure representing the pattern and organization between all the concepts of the subject in the student's long-term memory is called the "cognitive structure" (Tsai, 2001; Tsai and Huang, 2002). As a result, it can be said that while semantic memory expresses where and how the information is stored, the cognitive structure represents the organization of this information and the way it is interpreted. Accordingly, cognitive structures can help us learn how much students have understood the subject after instruction, as they show us how well students have established relationships between concepts. In other words, information about conceptual understanding is more related to the cognitive structure. Therefore, exploring the cognitive structures of learners at various stages of the course can be used in planning instruction or evaluating students' achievements.

To explore cognitive structures, researchers have developed a range of approaches. While some approaches focus on understanding students' cognitive structures individually, others are geared toward mapping the cognitive structures of groups. Approaches such as concept maps (Brandt *et al.*, 2001; Nakiboğlu and Ertem, 2010) and flow diagrams (Tsai, 2001; Zhou *et al.*, 2015) are typically used to represent individual cognitive structures. WAT is one of the most widely used approaches for mapping group cognitive structures, particularly in science education (Deese, 1965; Shavelson, 1973; Bahar *et al.*, 1999; Nakiboğlu, 2008; 2023, 2024). Rooted in theories of semantic memory, WAT operates on the assumption that the sequence, frequency, and variety of responses retrieved from long-term memory in response to a stimulus word reflect the structure, strength, and accessibility of knowledge (Shavelson, 1972; Jonassen, 1993). By eliciting free and spontaneous associations, WAT captures underlying conceptual relationships—both accurate and flawed—that learners use to organize and interpret scientific content (Gussarsky and Gorodetsky, 1988). Unlike traditional assessments, WAT enables a relatively unbiased and unprompted reflection of learners' mental models, allowing for the visualization of semantic proximity, conceptual density, and structural coherence (Wagner *et al.*, 1996; Hovardas and Korfıatis, 2006). In this way, the technique provides valuable insights into not only the content of conceptual knowledge, but also how well that knowledge is connected, integrated, or fragmented (Sutton, 1980).

WAT has been widely used to track conceptual change before and after instruction (Shavelson, 1972; Cachapuz and Maskill, 1987; Hovardas and Korfıatis, 2006). For instance, in their study on students' understanding of reaction kinetics, Cachapuz and Maskill (1987) reported that although learners had no formal instruction in the topic, their WAT pre-test responses indicated limited prior knowledge. After instruction, post-test networks became noticeably more complex, with fewer isolated clusters, indicating that conceptual learning had occurred. Similarly, Hovardas and Korfıatis (2006) adopted a social representations framework to explore conceptual restructuring. They argued that the representational meaning of stimulus words changed after instruction, signalling deeper semantic reorganization. Importantly, they also noted that WAT allows for relatively unbiased longitudinal assessment and is effective for identifying evolving conceptual patterns over time. Additionally, WAT has been used to evaluate the impact of instruction on conceptual networks, as seen in Nakiboğlu's (2008) post-instructional work on atomic structure, and to compare students' conceptual organizations across grade levels, as in Nakiboğlu (2024), who analysed differences in how physical and chemical changes were understood by learners at different educational stages.

In chemistry education, WAT has been used to explore a wide range of topics. Nakiboğlu (2008) examined students' associative networks concerning the atom, revealing that the structure and richness of associations correlated with instructional outcomes. Her more recent studies (2023, 2024) focused on persistent misconceptions about physical and chemical changes and illustrated conceptual differences across age groups. Derman and Eilks (2016) investigated students' understanding of dissolution, finding unidirectional and fragmented links in conceptual maps. Şen *et al.* (2019) applied WAT to analyse learners' structures concerning reaction rates and chemical equilibrium, while Baptista *et al.* (2019) explored associations related to the saponification reaction, identifying common misconceptions and weak concept integration. Most recently, Derman *et al.* (2024) combined WAT with free writing to study students' understanding of acid–base chemistry. Their analysis showed that although a variety of concepts were activated, cross-connections among key terms remained sparse, and the resulting structures were largely static and linear, indicating a lack of coherent integration.

Beyond its diagnostic applications, WAT is also sensitive to cognitive styles and learner characteristics. Bahar and Hansell (2000) found that divergent thinkers produced significantly more diverse and numerous associations than convergent thinkers, suggesting that conceptual fluency and ideational flexibility strongly influence WAT performance. Interestingly, no significant differences were observed between field-dependent and field-independent learners, implying that WAT reflects semantic memory depth more than the ability to isolate contextually embedded information.

WAT is also one of the most widely used approaches for mapping group cognitive structures (Bahar *et al.*, 1999; Nakiboğlu, 2008, 2023, 2024). As cited by Shavelson (1972), the fundamental idea underlying WAT is that the order in which responses are retrieved from long-term memory reflects a significant portion of the structure within semantic memory and the relationships between concepts. Mapping the connections between stimulus and response words allows researchers to visualize learners' conceptual systems, including central nodes, peripheral concepts, and misaligned associations. These maps serve as powerful tools for identifying conceptual strengths, weaknesses, and misconceptions in a content area.

In the present study, WAT was utilised to investigate the semantic closeness among electrochemistry concepts and to construct group cognitive structure maps of PSCTs. This approach aimed to illuminate the conceptual networks' content, organisation, and coherence underlying their understanding of electrochemistry.

Within this framework, the study does not focus on evaluating the scientific accuracy of individual concepts but rather seeks to uncover the structural features of how these concepts are cognitively interconnected. The identification of central concepts, as well as the absence, weakness, or fragmentation of expected associations, provides insights into the coherence and depth of learners' conceptual organisation. Although the concepts elicited through WAT were not categorised as canonical or alternative, such structural patterns may indirectly reflect conceptual instability or the presence of alternative conceptions. Thus, the cognitive maps derived from WAT are interpreted not as normative models of expert knowledge but as diagnostic representations of the participants' internal conceptual frameworks.

Students' alternative conceptions about electrochemistry

An examination of the literature on electrochemistry education reveals the prevalence of alternative conceptions among students and these can be broadly categorized into electric circuits (including principles such as the charge balance, potential difference and electric current), redox reactions (encompassing oxidation numbers and states, and charge), both chemical and electrochemical equilibrium, and electrochemical cells (involving current flow in electrolyte solutions, galvanic cells, electroneutrality, salt bridges, electrolysis, and concentration cells) (Nakiboğlu *et al.*, 2024).

Garnett and Treagust (1992a), researchers working on electric circuits, stated that to understand galvanic and electrolytic cells well, first of all, electric circuits should be well understood, based on the findings of the study carried out with Australian students, it was determined that students held misconceptions in three particular areas: charge law, electric current and potential difference. Özkaya (2002), working with Turkish chemistry teacher candidates, determined that they had difficulty understanding the concept of half-cell potential. Bradley and Moodie (2023) examined the problems related to plus and minus signs in the context of electrochemical cells and circuits.

Another important alternative conception group is related to the reduction–oxidation reactions, and they are one of the fundamental prerequisites to understand of the electrochemical cells (Garnett and Treagust, 1992a). For instance, students were found to struggle with distinguishing between oxidation state and charge, which led to errors in balancing redox reaction equations (Bischoff *et al.*, 2010; Brandriet and Bretz, 2014; De Jong *et al.*, 1995; Basuki, 2020).

We categorized the third group of difficulties and alternative conceptions concerning electrochemistry under the theme of electrochemical cells. This group is the group with the most alternative concepts regarding electrochemistry. The topics and concepts studied in this group and where the problems are determined are electroneutrality, current flow in the electrolyte solution and salt bridge, electrolysis, working principle of electrolysis cells, the configuration of a voltaic cell's components and their respective functions, the difference between electrolytic and galvanic cells, and concentration cells (Garnett and Treagust, 1992a, b; De Jong and Treagust, 2003; Rahayu *et al.*, 2011; Tsaparlis, 2018; Lu *et al.*, 2020; Nakiboğlu and Nakiboğlu, 2022; Nakiboğlu *et al.*, 2024). Researchers also identified many alternative conceptions concerning electrochemistry, and some examples of them are as follows. Rahayu *et al.* (2011) revealed that the students assumed that electron flow occurs through the electrolyte solution and the salt bridge. Similar results were obtained from the study practised with Turkish 12th-grade students using the same test (Nakiboğlu *et al.*, 2024). The study by Sanger and Greenbowe (1997b) with USA students also exposed similar alternative conceptions regarding salt bridges and Lin *et al.* (2002) with Taiwanese students. Lin *et al.* (2002) detected that learners perceived the principle and function of the salt bridge to be similar to those of the copper wire. One of the learners' problems regarding the function of voltaic cells is related to the anode and cathode. Sanger and Greenbowe (1997a) identified that students believed the anode was positively charged because it lost electrons, while the cathode was negatively charged due to the gain of electrons.

In relation to alternative conceptions about electrolysis, Garnett and Treagust (1992a, b) found that learners held the misconception that the anode was negatively charged and therefore attracted cations, whereas the cathode was positively charged, attracting anions. Additionally, Sanger and Greenbowe (1997b) indicated that learners assumed identical reactions would occur at both electrodes when the same type of electrodes was used in electrolysis.

Birss and Truax (1990) cited that a notable challenge concerning electrochemistry involves the equilibrium concept, attributing difficulties with understanding equilibrium potential to language issues. Özkaya (2002) examined the level of understanding of Turkish PSCTs for galvanic cells regarding the difference between chemical and electrochemical equilibrium and the alternative conceptions they might hold. He revealed that subjects of the study believed that when a metal is immersed in an electrolyte containing its ions, the electrical potentials of the metal and the electrolyte equalize due to the establishment of electrochemical equilibrium between the metal and its ions in the electrolyte.

From above explanations made so far, the conceptual understanding and alternative conceptions of students at different levels regarding electrochemistry have been investigated. Additionally, it is critical to uncover the students' cognitive structures concerning electrochemistry and to understand the relationships between the key concepts in this field. Although no study reveals the relationships between the basic concepts of electrochemistry using the WAT and simultaneously examines and compares students' alternative conceptions of all these concepts, some studies have compared either the cognitive structure alone or both the cognitive structure and alternative conceptions of students for some electrochemistry topics (Bischoff *et al.*, 2010; Loh and Subramaniam, 2018a, b). In these studies, techniques such as open-ended questions and flow diagrams were used to reveal the cognitive structures.

Loh and Subramaniam (2018a, b) evaluated the students using an open-ended question to identify their knowledge structure on galvanic cells. At the end of their study, they mapped students' knowledge structure, which included both canonical concepts and alternative conceptions concerning galvanic cells. They found that students could incorrectly use correct chemistry concepts by inappropriately establishing linkages among the concepts related to galvanic cells. Based on their findings, they emphasized that although it is important to evaluate students' alternative conceptions, it is also important to evaluate the concepts and connections between concepts in students' knowledge structure so that teaching can be made more effective.

Bischoff *et al.* (2010) investigated the evolution of preservice science teachers' knowledge structures in the area of oxidation and reduction chemistry. They obtained the preservice science teachers' knowledge structures through video-recorded semi-structured interviews before and after the instruction and analysed using a visual flow map representation.

Aims of the study and research questions

As outlined in the introductory section of this study, the primary aim was to compare the findings obtained from two different assessment tools, evaluate the degree of overlap between these findings, and examine whether there is a relationship between PSCTs' conceptual understanding of electrochemistry and their underlying cognitive structures. Both the ECT and the WAT employed in this study have previously been administered to upper secondary students. The conceptual knowledge targeted by the ECT represents a fundamental component of the upper secondary chemistry curriculum. Therefore, it is critical that PSCTs, who are expected to teach electrochemistry at this level, possess a well-structured conceptual understanding of these topics. In addition, based on cognitive structure mapping and semantic proximity relationship mapping, seeing to what extent some concepts that students find close to each other in their semantic memories can take place in the context of the knowledge structure pattern can also guide those who do cognitive studies.

A secondary aim of the study emerged from this context: comparing the results obtained from PSCTs with those of upper secondary students. Such a comparison offers a valuable perspective, potentially revealing whether PSCTs encounter conceptual difficulties similar to those experienced by high school students. In turn, this may help determine whether the challenges associated with learning and teaching electrochemistry persist across educational levels, thereby providing a stronger foundation for realistic and targeted pedagogical recommendations for both teachers and teacher educators. In line with these objectives, the sub-research questions guiding the study are presented below.

• How do PSCTs organize key electrochemistry concepts within their semantic memories, and what is the level of interconnectedness among the key concepts?

• What associations do the group cognitive structures of PSCTs form between the stimuli concepts of the electrochemistry and the response concepts related to these concepts?

• What is the overall level of PSCTs' comprehension of electrochemical concepts, what are their correct response rates on the electrochemistry concept test?

• How consistent is the PSCTs' conception of electrochemical concepts with the five conceptual groups and what are their alternative conceptions of these groups?

• To what extent do the findings derived from the WAT support or confirm the results obtained from the ECT, particularly in relation to the conceptual categories of electrochemistry?

Methods

As this study aims to investigate whether there is a relationship between the results of qualitative and quantitative data from different perspectives, as well as how these data complement each other, the study is a *mixed research study*. Tashakkori and Creswell (2007) define mixed method research as research in which the researcher collects and analyses data, integrates the findings and draws inferences using both qualitative and quantitative approaches or methods in a single study or research program. Creswell, Plano (2011) emphasized that the basic premise of mixed method research is that the use of quantitative and qualitative approaches together provides a better understanding of research problems than either approach alone.

There are four basic mixed method designs (Creswell and Plano, 2011). The current study was conducted according to one of these four methods, the *convergent parallel design*. Convergent parallel design occurs when the researcher uses simultaneous timing to apply quantitative and qualitative stages at the same stage of the research process, gives equal priority to the methods, and keeps the stages independent during the analysis, and then mixes the results during the overall interpretation (Creswell and Plano, 2011).

In this study, two different data sets were collected simultaneously from the same study group in order to investigate the relationship between PSCTs' conceptual understanding of electrochemistry and their cognitive structures. For this purpose, different sub-research questions were developed and within the scope of the theoretical structure, explanations were given under the same learning theory, one focusing on conceptual understanding and the other on cognitive structure and revealing the relationship between them.

Participants

In this study, a *purposeful convenience sampling method* was employed (Patton, 2002). The sample was drawn from the Chemistry Education Department at the Education Faculty of a Turkish Public University. This department offers a chemistry teacher training program, which is a four-year integrated curriculum where PSCTs simultaneously take both chemistry and pedagogical courses. The primary objective of this program is to equip PSCTs with the necessary knowledge and skills to teach chemistry at four-year upper secondary schools. In addition to core chemistry education courses, the program includes specialized chemistry teaching methods courses, as well as other essential pedagogical courses such as educational psychology, curriculum development, and measurement and evaluation, all of which are fundamental for preparing future chemistry teachers. The 80 PSCTs, 57 females and 23 males, who completed the electrochemistry course in different years participated in the study. In the WAT test, one PSCT was not included in the analysis because it did not fill more than half of the test. Therefore, the number of study groups for WAT was 79. All PSCTs completed General Chemistry I and II during their first year of university studies. Electrochemistry-related topics were taught at a basic level in the General Chemistry II course that the PSCTs took during their freshman year. The electrochemical process is taught in detail in the Analytical Chemistry II course again. Finally, all PSCTs attended the electrochemistry course in the initial term of the third year. All data were collected during the first semester of the fourth year (7th semester) of education from PSCTs who were in their final year between 2018 and 2022. The 7th semester was chosen to evaluate the extent to which students retained electrochemistry concepts after completing all relevant coursework before graduation. Additionally, it aimed to determine whether certain alternative conceptions persisted despite their prior instruction.

Necessary permissions were obtained from the Balıkesir University Ethics Committee for the study. Before application, the participants were duly informed by the authors regarding the objectives of the study, and assurances were made regarding their anonymity when the results were to be disclosed. All students involved in the study participated voluntarily and gave their informed consent.

Instruments and data collection

Data were gathered through the use of two instruments: a WAT and an Electrochemistry Concept Test analysis (ECT). How each test was developed and implemented is explained under separate sub-headings below.

The development and application of the WAT. In the development of the WAT, the initial step involved selecting the key concepts that would serve as stimuli. In the studies conducted, the number of stimulus words used in the WAT ranges from eight to twelve, with the variation depending on the specific structure of the subject being examined. However, it is also essential to ensure that the generated maps do not result in an overly complex and difficult-to-interpret structure. Therefore, conducting a preliminary study on the expected relationships between key concepts and the anticipated response concepts for each key concept—an approach that also informs the interpretation process during analysis—enhances the validity of the test. During the selection of stimulus words for the WAT, a commonly employed another method involves identifying frequently used concepts in teaching the subject matter, particularly those that serve as fundamental models for the structure of the topic (Johnson, 1967; Nakiboğlu, 2023). In this study, the first author (CN) initially identified and selected the key concepts that would serve as the foundation for conceptual understanding in electrochemistry. Following this, the second author (NN) reviewed and confirmed that these concepts were indeed fundamental. Since the WAT is also employed to assess students' knowledge of electrochemistry at the upper secondary school level, the initial development study was conducted for 12th-grade students. To this end, the 'Chemistry and Electricity' unit of the high school chemistry curriculum was reviewed by the authors. Expert judgment was obtained from an experienced high school chemistry teacher. Following the establishment of content validity, the test was administered to 12th-grade students for evaluation (Nakiboğlu and Nakiboğlu, 2018a). Subsequently, all concepts were reviewed and revised by the authors to ensure their suitability for application at the university level.

To further ensure validity, an additional faculty member specializing in electrochemistry examined the selected concepts. Upon receiving their approval, it was concluded that the WAT demonstrated content validity. Furthermore, the authors later conducted an additional study to explore the expected relationships between key concepts and the anticipated response concepts for each, which would be utilized in the interpretation process during the analysis.

The number of stimuli (key) was determined as 10. The stimuli concepts of the present study are electrolyte, anode, cathode, electrode, reduction, oxidation, salt bridge, electrolysis, conductivity, and electrochemical cell. The possibility of including "galvanic cell" as the 11th most frequently used concept was also considered by the authors. However, it was anticipated that participants would infer the concept of "galvanic cell" based on the provided key concepts. Similarly, the concept of "cell" was deliberately excluded, as it was expected that participants would arrive at this concept through associative reasoning. The first author had previously determined in an earlier study (Nakiboğlu, 2008) that participants could successfully reach these expected concepts by following a similar cognitive pathway. In the study conducted by Nakiboğlu and Nakiboğlu (2018a) with 12th grade students, it was determined that students connected the concepts with "cell" and that it emerged as the central concept in the cognitive structure, which confirmed this situation.

The PSCTs were given a booklet, with each page featuring one of the ten stimulus concepts. To minimize potential distractions, each stimulus concept was repeated ten times, listed sequentially on the page. A designated space was provided next to each concept for the participants to write their response word (Shavelson, 1974). During the data gathering with WAT, the booklet was delivered to the PSCTs, accompanied by a detailed explanation regarding the completion process. The participants were instructed that each page of the booklet contained a distinct concept and that it was written ten times, they were informed that they would be given 30 seconds to write answer words for a concept on each page. This optimum time span was favoured because it is a time used in many studies (Bahar and Hansell, 2000; Cordellini and Bahar, 2000). The repetition of each stimulus concept ten times aimed to elicit a wide range of associative responses and enhance the reliability of the data by reducing the effect of random or isolated answers, which is a common practice in word association research. They were warned that the answer concepts should be chemistry-related and that they should not write sentences. After the time given for each concept was completed, they were informed that they would be instructed to "move on to the next concept". The course instructors facilitated the administration of the WATs and monitored the allotted time for completion. To avoid potential influence of the ECT on participants' responses, the WAT was administered first to the PSCTs before the ECT.

The development and application of the ECT. The ECT, created by Rahayu *et al.* (2011) based on the Indonesian high school chemistry curriculum, served as the second tool for data collection. Before the study, permission for use was requested from SR. The authors had previously adapted the ECT into Turkish and used it to measure the conceptual understanding level of 12th-grade students (Nakiboğlu *et al.*, 2024). In the present paper, we present the adaptation process in detail again, in order to provide the reader with full perspective and to clarify the methodological steps relevant to this study's context.

In the study of Nakiboğlu *et al.* (2024), for the adaptation, the ECT was translated into Turkish independently by the researcher CN and a doctoral student, after which both translations were compared, integrated, and refined. The initial edited version was reviewed by a chemistry educator proficient in English to ensure linguistic accuracy and conceptual equivalence. Subsequently, Version 2 was re-evaluated by the second author of the study and electroanalytical chemistry expert NN to ensure the appropriateness of the expressions, after which it was finalized. Finally, two experienced chemistry teachers, one with a master's degree and the other with a doctoral degree, reviewed the test, confirming that the questions demonstrated content validity. As part of the original adaptation process in Nakiboğlu *et al.* (2024), content validity for use at the upper secondary level was established by first reviewing the Turkish Secondary School Chemistry curriculum to confirm that all theoretical concepts covered in the ECT were indeed included at that level. This step was essential because, if certain concepts were absent from the curriculum, students would lack the prerequisite knowledge to respond meaningfully to the items. The test was first administered to a pilot group of approximately 20 students from one 12th-grade class. After completing the test, these students were asked for feedback on the clarity of the instructions and the wording of the items, and they reported no difficulties in understanding the questions. Based on this confirmation, the test was subsequently administered to additional classes from various secondary schools, bringing the total sample to 56 12th-grade students. In Türkiye, upper secondary school covers four years (grades 9–12) and typically includes students aged 15 to 18; 12th-grade students are generally around 18 years old. Since the present study focuses on PSCTs, a different target population from the original adaptation, an additional suitability check was conducted before applying the ECT at the university level. This was done through a content review by another faculty member who taught the electrochemistry course, along with the second author NN, who, although PSCTs had completed coursework covering all relevant concepts, noted that some subtopics may be taught with varying depth depending on the course instructor. Therefore, obtaining the course instructor's feedback ensured the suitability of the ECT for this specific context and further reinforced the validity of the instrument (Lawshe, 1975).

The reliability analysis of the test was conducted with upper secondary school students. The original version of the ECT, developed by Rahayu *et al.* (2011), demonstrated a Cronbach's alpha reliability coefficient of 0.63. In the comparative study involving Turkish students, this value was found to be 0.59. Both values exceed the threshold of 0.50, as recommended by Nunnally and Bernstein (1994), as cited in Sia *et al.* (2012). Although a commonly accepted standard for high reliability is $\alpha \geq 0.70$, it has been noted that Cronbach's alpha may not always be the most appropriate measure of reliability for all types of assessments (Brandriet and Bretz, 2014). Additionally, Adams and Wieman (2011) have argued that lower reliability values can be acceptable for formative assessment tools designed to evaluate instructional effectiveness. Therefore, alternative reliability measures were examined. In this context, Ferguson's delta (δ) values for the ECT were calculated. Ferguson's delta is a measure of the discriminatory power of test scores, indicating the extent to which students' scores are distributed across the total possible score range. A test is considered to have sufficient discrimination if Ferguson's delta meets the criterion of $\delta \geq 0.90$ (Brandriet and Bretz, 2014). In this study, the Ferguson-δ value was found to be 0.954, indicating a high level of discrimination.

Table 1 Groupings of questions in the ECT

The groups	Question no
Reactions occurring during electrolysis	1, 2, 17
Differences between electrolytic and voltaic cells	3, 4, 9, 18
Movement of ions in voltaic cells	5, 7, 8, 10
Poles in voltaic cells	11, 12, 13, 14
Voltaic cell reactions	6, 15, 16

The ECT consists of a total of 18 multiple-choice questions, 16 of which are four-choice and two of which are two-choice, divided into five distinct categories. There is only one correct option in each question, and one or more of the other options consist of statements containing alternative concepts. The specific categories, along with their respective question numbers, are presented in Table 1.

As seen in Table 1, the first category of the ECT, reactions occurring during electrolysis, includes three questions Q1, Q2 and Q17. The questions in this category examine students' understanding and misconceptions regarding the reactions occurring during electrolysis. A question in this category (Q1) is given below as an example. (The correct answer to each question is shown in bold.)

Diagram 1 shows an electrolytic cell for the electrolysis of dilute hydrochloric acid. Use this diagram to answer questions 1 and 2.

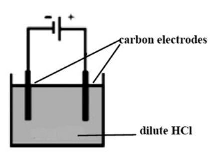


Diagram 1

1 Which of the following statements is true?

1) HCl is decomposed by electrolysis into H^+ and Cl^- ions.
2) H_2 is formed at the negative terminal, Cl_2 at the positive terminal.

A (1) only
B (2) only
C (1) and (2)
D Neither (1) nor (2)

The second category of the ECT, differences between electrolytic and voltaic cells, also includes four questions: Q3, Q4, Q9, and Q18. Q9 from this category is given below as an example.

"Q9. Which is the correct statement about a voltaic cell and an electrolysis cell?

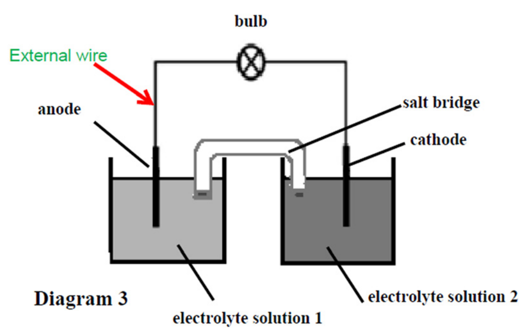
A. The cell reaction can occur spontaneously in both voltaic and electrolysis cells.

B. In the voltaic cell, electrical energy changes into chemical energy whereas in the electrolysis cell, chemical energy changes into electrical energy.

C. *In the electrolysis cell, electrical energy changes into chemical energy whereas in the voltaic cell, chemical energy changes into electrical energy.*

D. The cell reaction in a voltaic cell needs an electrical current, whereas the cell reaction in an electrolysis cell does not need an electrical current.''

The third category of the ECT, movement of ions in voltaic cells, includes four questions: Q5, Q7, Q8, and Q10. Q8 from this category is given below as an example.



''Q8. Diagram 3 shows a voltaic cell with a salt bridge and electrolyte solutions within each of two half-cells. Which of the following statements is correct about the result of using a salt bridge in the voltaic cell?

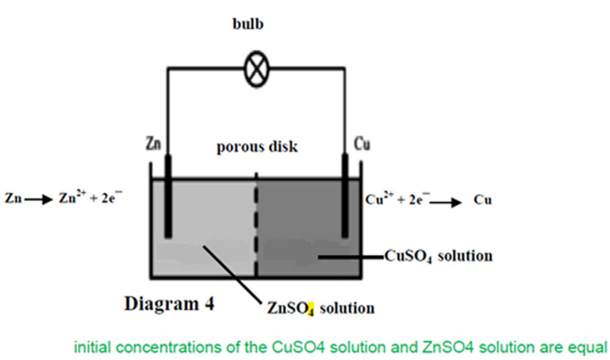
A. The solution around the cathode will be acidic whereas the solution around the anode will be basic.

B. The solution around the cathode will be basic whereas the solution around the anode will be acidic.

C. The numbers of cations and anions in the two half-cell are always the same.

D. *The total electric charge of the cations and anions in the two half-cell is always the same.*

The fourth conceptual category of the ECT, poles in voltaic cells, includes four questions: Q11, Q12, Q13, and Q14. Q11 from this category is given below as an example.



''Q11 Which of the following statements is true?

The cathode is......

A. The electrode at which positive ions accept electrons (reduction). It is the negative pole of the cell.

B. *The electrode at which positive ions accept electrons (reduction). It is the positive pole of the cell.*

C. The electrode from which electrons flow away into the external circuit (oxidation). It is the negative pole of the cell.

D. The electrode from which electrons flow away into the external circuit (oxidation). It is the positive pole of the cell.

The final conceptual category of the ECT, voltaic cell reactions, includes three questions: Q6, Q15, and Q16. Q6 from this category is given below as an example.

''Q6 Which is the correct statement about the half-cells of a voltaic cell?

A. The place where oxidation and reduction reactions occur.

B. The place where oxidation and reduction reactions occur separately at different times.

C. *The place where the oxidation and reduction reactions occur at the same time.*

D. The place where oxidation and reduction reactions occur separately to form positive and negative ions which are soluble in the electrolyte solution.

ECT consists of 18 multiple-choice items designed to assess students' conceptual understanding of fundamental electrochemical principles.† To determine whether the test adequately meets this objective, each item was analysed using Revised Bloom's Taxonomy (Anderson and Krathwohl 2001). The results of this analysis are presented in Table 2.

As shown in Table 2, 16 out of the 18 items are categorized at the ''Understanding'' level or higher, while only 2 items (Items 7 and 14) fall under the ''Remembering'' level. This indicates that the ECQ is not limited to rote memorization but is structured to engage students in conceptual interpretation, relational reasoning, and knowledge transfer to new contexts. Thus, the test successfully meets its goal of targeting conceptual understanding. Although two items (Items 14 and 17) include only two answer choices—potentially increasing the probability of correct responses by guessing—their impact on the overall validity of the instrument is minimal. Item 17, in particular, is embedded within a diagram-based cluster, requiring students to engage in contextual reasoning rather than isolated recall. Therefore, even though the binary format may appear limited on the surface, the cognitive demand of the item remains appropriate. Furthermore, the interpretation of student responses was conducted in relation to the conceptual categories of the test. Each item was grouped under specific conceptual areas such as electrolysis, ionic conduction, salt bridge function, electrode behavior, and redox processes. When the test is evaluated holistically across these conceptual categories, it is evident that no category relies solely on two-choice items, and both two-choice items are marginal within the broader conceptual structure. This reinforces that the binary items do not play a determining role in shaping the interpretation of students' cognitive frameworks. According to aforementioned explanation, the ECT can be considered a conceptually coherent and cognitively valid assessment tool. The inclusion of two binary items presents a minor limitation that was addressed methodologically and did not substantially affect the test's capacity to provide meaningful insight into students' cognitive structures in electrochemistry.

† Only the questions that were published in Rahayu *et al.* (2011) are presented here; no further or unpublished items are shared.

Table 2 Classification of ECT questions based on revised bloom's taxonomy

Conceptual category no	Question number	Bloom level	Question content	Explanation about assigned bloom level
1	1	Understanding	Dissociation of HCl and gas evolution at electrodes.	Requires interpreting conceptual statements, not mere recall.
	2	Applying	H^+ ions gaining electrons to form H_2.	Involves applying knowledge of ion behaviour to a specific electrolysis context.
	17	Applying	Identifying negative electrode based on given reactions.	Requires applying redox understanding to identify electrode polarity.
2	3	Understanding	Movement of current through solution.	Involves understanding the distinction between electron and ion conduction.
	4	Applying	Direction of electron flow in a voltaic cell.	Requires transferring theoretical knowledge to interpret a diagram.
	9	Understanding	Energy transformations in voltaic *vs.* electrolytic cells.	Requires comprehension and comparison of two related concepts.
	18	Understanding	Charge transport in $CuCl_2$ solution.	Understanding the mechanism of ionic conduction is necessary.
3	5	Understanding	Direction of ion flow in the salt bridge.	Requires conceptual grasp of charged particle migration in context.
	7	Remembering	Type of electrolyte used in the salt bridge.	Pure recall of a specific factual detail.
	8	Understanding	Salt bridge effect on charge balance.	Requires interpreting the chemical role of the salt bridge in maintaining neutrality.
	10	Applying	Ion flow through a porous disk.	Application of knowledge to a diagram-based scenario.
4	11	Understanding	Definition and polarity of cathode	Requires linking abstract concepts with physical properties.
	12	Understanding	Cation movement toward electrodes.	Requires understanding of charge-pole interactions.
	13	Analysing	Determining correctness of multiple statements.	Involves analysing and evaluating conceptual accuracy.
	14	Remembering	Identifying the negative electrode.	Straightforward factual recall.
5	6	Understanding	Redox processes in half-cells.	Understanding the spatial and temporal aspects of oxidation and reduction.
	15	Understanding	Location of electrochemical reactions.	Requires understanding where chemical processes occur in a cell.
	16	Understanding	Role of inert electrodes.	Requires conceptual comprehension of chemically active *vs.* inert materials.

Data analysis

WAT analysis. To address the first two research questions, various analyses were conducted. Yet, the response frequency analysis was first performed in order to make calculations for both the first and second research questions and to produce data for the map drawings. Subsequently, additional analyses were conducted by utilizing the response frequency data in an alternative manner. In the following sections, the methodology for response frequency analysis is first outlined under a separate sub-heading. Next, the procedures for the remaining analyses, which address each research question, are described, along with the construction of two different mapping approaches.

The first map generated addresses the first research question, and this is *the semantic relatedness map*, which illustrates the semantic proximity of the key concepts given in the semantic memory. This analysis was made to determine how similar the 10 concepts related to electrochemistry were placed in the semantic memory of the students in terms of meaning. The second map is used to answer the second research question, and thus, it is aimed to determine how the students connected the 10 stimulating concepts given about electrochemistry with other concepts of the subject, that is, to determine *the cognitive structure.* Below, both the path followed in the analyses made in the first step of these mappings and the methods used to create the maps are explained under separate headings.

The response frequency analysis. At this stage, the concepts generated by students in response to each stimulus word, referred to as "response concepts/words," were individually counted and recorded in Excel. The term "response concepts/words" denotes the concepts or words that students associated with the given stimulus concept in the WAT. The response frequency data obtained in this initial step served as the foundation for two subsequent analytical methods.

The semantic relatedness analysis. To address the first research question, the relatedness coefficient (RC) analysis proposed by Garskoff and Houston (1963) (cited in Bahar *et al.*, 1999), was employed. This method quantifies the degree of overlap between the response concepts associated with two different keywords. In this study, RCs were calculated to examine how PSCTs link one key concept to another within their semantic memory. The formula developed by Garskoff and Houston (1963) yields a RC ranging from 1 (indicating perfect relatedness, such as synonyms) to 0 (indicating no relationship). The simplified version of this formula, along with its explanation, is provided below as adapted from Bahar *et al.* (1999). For a more detailed understanding of the specimen calculation, the referenced study can be consulted.

$$\text{RC (relatedness coefficient)} = \frac{\bar{A} \cdot \bar{B}}{(A \cdot B) - 1}$$

In this formula, ***A*** denotes the rank order of words that appear under concept *A* and are also shared with concept ***B***, while ***B*** represents the rank order of words under concept ***B*** that are likewise shared with concept ***A***. The term ***A·B*** refers to the sum of the products of the rank order of each common word in ***A*** and its corresponding rank order in ***B***, calculated for all overlapping words.

The RC values were calculated using excel. For the purpose of ensuring the reliability of the analysis, the first author performed the calculations independently at different times and repeated the process twice. Although the first author determined that the results of both calculations were exactly the same, the second author checked by randomly drawing from the calculations and found that there was no difference between all the selected calculations. The consistency of the results confirmed the reliability of the analysis. The derived relatedness coefficient values were then presented in a table.

The semantic relatedness mapping method. A map illustrating the relatedness between the stimulus concepts in the semantic memory was constructed using the cut-off point mapping method (Bahar *et al.*, 1999) based on the RC values obtained. In this mapping method, only the stimulus concepts are retained as nodes and the connections represent how frequently these concepts appeared as responses to each other. The map helped determine the relationships between the stimulus concepts related to electrochemistry concepts in the semantic memories of the PSCTs, as well as the degree of interconnectedness among these stimulus concepts. In this graph-based mapping method, the stimulus (key) concepts are represented as points, with their relationships depicted as lines. The proximity between concepts is indicated by the lines, and appropriate cut-off points are selected during the creation of the structure. The thickness of the lines varies depending on the strength of the associations, with the thickest line representing the strongest relationship. The graph construction begins with the strongest RC value. For this study, 1.0 was chosen as the highest cut-off point, as the maximum value in the RC calculation was 1.0. As the graph was drawn, the cut-off point was progressively decreased until all relevant stimulus words appeared, based on the RC values.

The cognitive structure mapping method. To visualize the cognitive structures of PSCTs and to response the second research question, a map was generated based on response frequencies (Bahar *et al.*, 1999; Nakiboğlu, 2008, 2023, 2024). Before presenting the cognitive structure map, a sample frequency table (Table 4) will be provided in the findings section to facilitate an accurate interpretation of the map. There are various approaches to mapping cognitive structures using response frequencies. In this study, the mapping technique developed by Nakiboğlu (2008) was employed to represent the cognitive structures of PSCTs. The resulting map illustrates both strong and weak associations established in students' cognitive structures between key concepts (stimulus concepts from the WAT) and response concepts (concepts generated in response to the stimuli). In this mapping technique:

• Key concepts are displayed inside rectangular boxes, with different border thicknesses indicating response frequency levels. The thickest border represents the highest frequency range, while thinner borders denote progressively lower frequencies.

• Response concepts, which emerge in association with each key concept, are not enclosed in a frame to distinguish them from stimulus words.

• Arrows of varying thicknesses are used to depict relationships between concepts, with arrow thickness and direction determined by the response frequency table. This variation allows for a more nuanced interpretation of conceptual relationships.

The path followed while drawing the map is given below.

1. The highest response frequency value is identified, and the initial cell of the table is used to construct the first phase of the map.

2. Relationships at this level are represented by thick arrows, with the arrow direction indicating the direction of conceptual associations.

3. The response frequency range is then reduced by a factor of ten, and the next phase of the map is drawn inside the subsequent cell.

4. This process continues, progressively lowering the response frequency threshold, until all stimulus words are incorporated into the map.

5. Colour coding is sometimes used to enhance visualization; in this study, red was applied to indicate very weak associations.

This structured approach provides a detailed representation of how PSCTs associate key chemistry concepts, allowing for deeper insights into their cognitive structures and the strength of conceptual relationships.

Electrochemistry concept test analysis. The IBM SPSS 24.0 software package was used to analyse all the data. All data were initially entered into SPSS by an independent researcher, who subsequently reviewed each entry twice to identify and correct any potential errors, thereby ensuring complete accuracy. Following this, the authors of the present study independently reviewed the entire dataset and confirmed that all data had been entered with 100% accuracy. Once the accuracy of the data was confirmed, one of the study's authors (CN) and a graduate student conducted independent analyses of the SPSS data. A comparison of their results revealed complete agreement (100%), thereby ensuring inter-coder reliability (Gay and Airasion, 2000, p. 175).

The data entry for the responses to the ECT was performed in two distinct formats within SPSS. In the first entry, students who selected the correct option for each item were coded as "1," while those who selected an incorrect option were coded as "0." This dataset was used to generate findings related to the statistics of the ECT, the percentage and frequencies of PSCTs who answered each item correctly, and the number of PSCTs who responded correctly to all items within each of the five conceptual categories.

In the second format, data were entered based on the actual response options selected by each PSCT for every item. This dataset was used to identify the alternative conceptions associated with each conceptual group. Analysing the frequency of specific incorrect responses made it possible to determine the proportion of PSCTs who selected each distractor, thereby revealing the most prevalent alternative conceptions among participants. The alternative conceptions represented by these distractors were considered dominant. However, if other distractors within the same item also contained elements that supported the same alternative conception, they were likewise considered. Furthermore, the 'Alternative Conception Strength' (ACS) values for these items were calculated based on the concept of 'misconception strength' as proposed by Chen *et al.* (2020). Upon examining Chen *et al.*'s definition, it was found that the term 'misconception' was used interchangeably with 'alternative conception.' As the term 'alternative conception' was preferred in the present study, the concept of 'misconception strength' was adapted accordingly and referred to as ACS.

Chen *et al.* (2020) noted in their study that, in most multiple-choice questions, students' incorrect responses are not evenly distributed across all distractors. Rather, there is typically one incorrect option—referred to as the dominant distractor—that is selected most frequently by students. This pattern often reflects a common underlying misconception. The authors further stated that students who lack relevant knowledge but do not hold specific misconceptions are likely to guess randomly, leading to an approximately equal distribution across distractors. While the presence of a strong distractor is generally seen as undesirable in traditional academic testing, the study highlighted that distractor-focused multiple-choice items—each embedding at least one prevalent misconception—have been developed specifically to identify and investigate students' misconceptions in science education. For this purpose, the authors proposed calculating "misconception strength," defined as the percentage of students selecting the dominant distractor divided by the total percentage of students selecting all incorrect options. Based on this metric, items were categorized as reflecting either a strong misconception (misconception strength >0.5) or a weak misconception (misconception strength ≤ 0.5).

Findings

The findings are given below as separate subheadings to answer the research question.

Findings about the interconnectedness among the key concepts in semantic memory

The initial research question explores how PSCTs organize key electrochemistry concepts (stimuli) within their semantic memories. The key concepts' RC values were illustrated in Table 3. The RC of the key concepts in the long-term memories of PSCTs was mapped by using these RC values in Table 3. The semantic relatedness map obtained was represented in Fig. 1.

Altogether, Table 3 and Fig. 1 provide a stepwise visual and numerical representation of how students build conceptual connections in the domain of electrochemistry. The pattern of concept inclusion across varying thresholds offers insights into the hierarchical strength and organization of students' conceptual structures. For this reason, the findings in Table 3 and Fig. 1 are explained together below. An examination of the RC values in Table 3 reveals that the strongest conceptual link among the key concepts is between "electrolyte" and "electrochemical cell" (RC = 0.92). This high RC value indicates that students associate these two concepts very strongly, possibly due to the essential role of the electrolyte in the functioning of electrochemical cells. This relationship is represented in the first cell (*i.e.*, the upper-left corner) of Fig. 1, which corresponds to the highest RC value observed. Other relationships with RC values slightly above 0.80 are seen between "electrolyte" and "salt bridge", "electrolyte" and "electrolysis", "electrode" and "electrochemical cell", and electrolysis and electrochemical cell. These associations, presented in the subsequent cells of Fig. 1, suggest that students perceive meaningful connections among components that frequently co-occur in instructional settings or laboratory experiments.

At this stage, three more key concepts—electrode, salt bridge, and electrolysis—are added to the conceptual map. When the RC cut-off value is lowered to 0.70, four additional key concepts—conductivity, oxidation, reduction, and cathode—are also included. This expansion indicates that students' associative networks begin to include more abstract or indirect concepts once the threshold is reduced. At the 0.70 threshold, only anode remains unconnected.

As shown in Table 3, "anode" has its strongest association with a value of 0.69. Therefore, all new associations involving the key concept "anode" at the 0.69 cut-off point are added, and a new graph is created. The graph shown in the fourth cell also illustrates that "anode" is added to the map by being associated with another key concept, "reduction", and that a new association is established between "conductivity" and "electrochemical cell".

Findings about the associations between stimuli concepts and response concepts in in PSCTs' group cognitive structures

The second research question examines the associations that the group cognitive structures of PSCTs form between the

Table 3 The key concepts' relatedness coefficient values

	Anode	Cathode	Electrode	Reduction	Oxidation	Salt bridge	Electrolysis	Conductivity	Electrochemical cell
Electrolyte	0.66	0.67	0.45	0.75	0.75	0.83	0.83	0.75	0.92
Anode	—	0.64	0.67	0.69	0.48	0.61	0.58	0.51	0.67
Cathode	—	—	0.66	0.45	0.70	0.56	0.59	0.52	0.67
Electrode	—	—	—	0.66	0.68	0.70	0.73	0.72	0.84
Reduction	—	—	—	—	0.78	0.68	0.76	0.57	0.78
Oxidation	—	—	—	—	—	0.71	0.74	0.54	0.76
Salt Bridge	—	—	—	—	—	—	0.75	0.62	0.79
Electrolysis	—	—	—	—	—	—	—	0.64	0.84
Conductivity	—	—	—	—	—	—	—	—	0.69

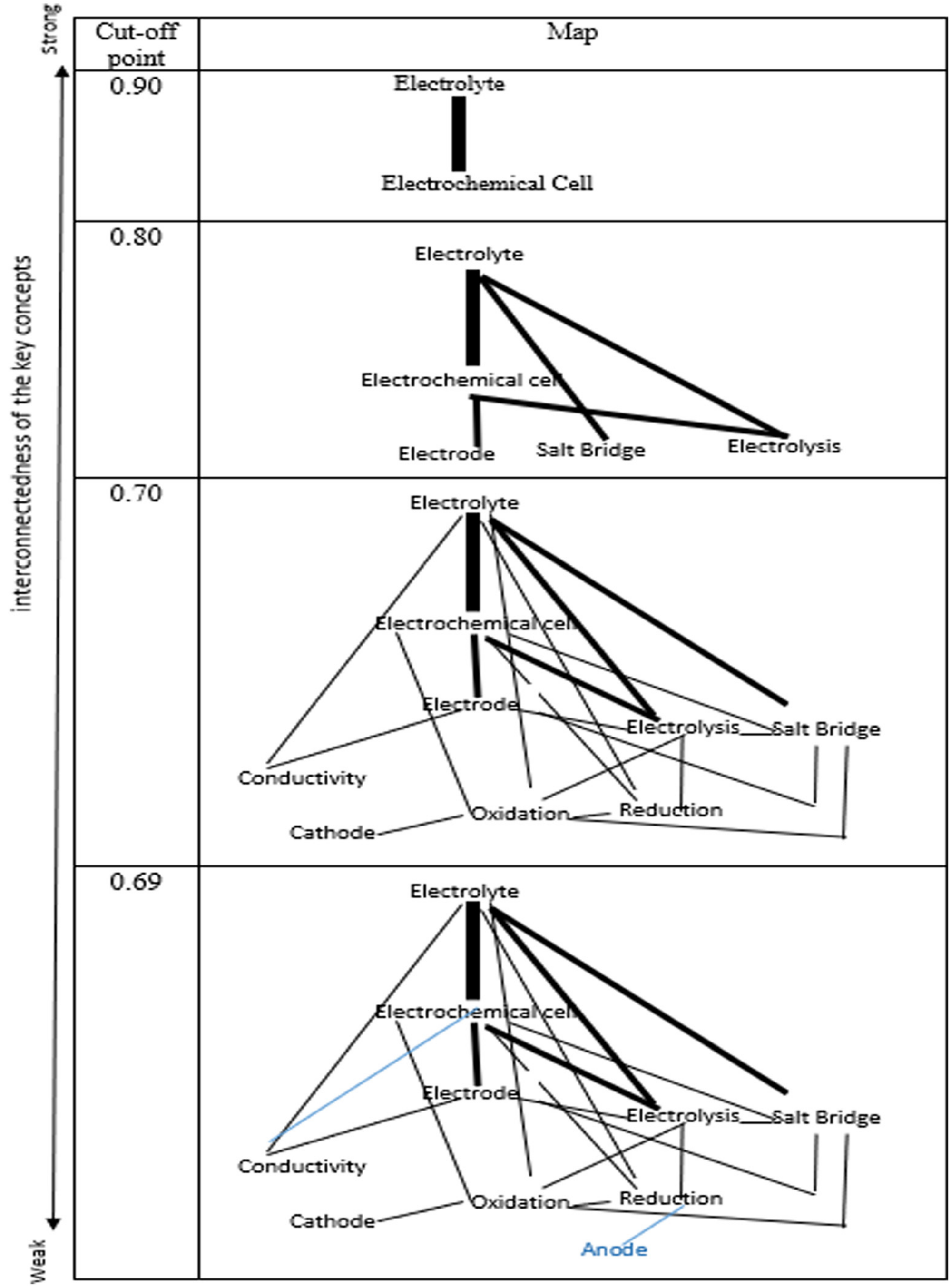


Fig. 1 The semantic relatedness map of the stimulus concepts about electrochemistry.

stimuli of the electrochemistry and the response concepts identified using frequency tables. In this context, a two-stage approach was used to address the research question: first, the extent of conceptual associations was explored through frequency data, and second, the structural relationships between these concepts were mapped visually. Table 4 presents the overall count of distinct response concepts for each stimulus concept of WAT and pertains to the ''extent,'' which is one aspect of describing cognitive structures as well.

As shown in Table 4, each stimulus word presented to explore the cognitive structures of PSCTs elicited between 257 and 364 subject-related response words. The stimulus concept ''Electrolyte'' has the highest number of distinct response types (75), whereas ''Electrochemical cell'' has the highest total response frequencies (364). The stimulus concept ''Reduction'' has both the lowest number of distinct response types (52) and the lowest total response frequencies (257).

Table 5 provides a representative example of the frequency table derived from the analysis of WAT. Afterwards, the PSCTs' group cognitive structures were mapped using data in Table 5.

Importantly, Fig. 2 is a direct graphical representation of the associations presented in Table 5. Each link between a stimulus

Table 4 The overall count of distinct response concepts for each stimulus concept

Stimulus concepts	Overall count of responses to a stimulus concept	Number of response concept types
Electrolyte	357	75
Anode	300	59
Cathode	306	73
Electrode	279	66
Reduction	257	52
Oxidation	292	59
Salt Bridge	299	69
Electrolysis	260	70
Conductivity	262	73
Electrochemical cell	364	59

and a response concept in the figure corresponds to an actual association identified in the frequency analysis. Thus, Fig. 2 does not represent a separate or interpretive analysis; rather, it visualizes the associative patterns embedded in the table. For this reason, Fig. 2 and Table 5 should be interpreted in conjunction with one another, as they together provide a comprehensive answer to the second research question. While Table 5 presents the numerical structure of associations, Fig. 2 translates those into a conceptual map that reflects the group-level cognitive structure of PSCTs in the domain of electrochemistry.

When Table 5 is examined, it is seen that the highest frequency values are 40 and above. Therefore, the first frequency range selected for mapping the cognitive structure is drawn for the associations corresponding to the frequency value of 40 and above (Fig. 2). In this frequency range, it is determined that there are two associations for the highest frequency value of 43. These are the relationships between the electrochemical cell and anode and the electrochemical cell and cathode. Another relationship in this frequency range is the connections from cathode to reduction and from reduction to cathode at 40. It is seen that the connections at this level only emerge between the key concepts and that no relationship emerges with any response concept. The next frequency range is taken as the range of $30 \leq f \leq 39$. When the associations in this frequency range are examined, it is seen from the map in Fig. 2 that the key concepts electrolyte, salt bridge and oxidation are added to the existing ones and that all key concepts are connected *via* the response concept "cell".

Once the frequency range is decreased to $20 \leq f \leq 29$, all of the stimulus concepts, with the exception of one, are integrated into the current map. The stimulus concept that does not appear at this level in the map is conductivity. For this reason, another drawing was made for 19, which is the highest frequency of this concept. Although the "conductivity" is encompassed in this

Table 5 A representative example of the frequency table concerning response concepts

Response concepts	Key (stimulus) concepts									Electrochemical cell
	Electrolyte	Anode	Cathode	Electrode	Reduction	Oxidation	Salt Bridge	Electrolysis	Conductivity	
Electrolyte	0	5	4	2	0	1	3	2	1	5
Anode	35	0	22	21	16	37	25	24	11	43
Cathode	35	25	0	19	40	14	26	24	12	43
Electrode	4	2	7	0	0	4	13	4	4	19
Reduction	7	10	40	5	0	14	4	6	2	11
Oxidation	6	37	11	7	14	0	4	6	2	13
Salt Bridge	23	15	17	19	7	6	0	10	10	35
Electrolysis	4	7	6	2	4	6	3	0	3	10
Conductivity	14	6	1	6	1	2	4	3	0	9
Electrochemical cell	2	1	1	0	1	1	1	1	0	0
Cell	36	27	27	23	14	16	23	17	12	31
Solution	28	5	9	11	4	8	17	6	6	12
Reaction	6	7	7	6	18	23	7	12	6	8
Positive charge	3	16	20	2	4	4	2	2	1	2
Negative charge	6	20	7	3	2	4	3	1	0	1
Copper	7	5	5	20	2	2	3	0	3	2
Ion	9	6	6	4	2	5	20	9	10	5
Metal	9	3	5	15	1	1	1	2	19	4
Water	1	0	0	0	0	0	0	19	0	0
Electron	12	12	11	9	17	11	8	8	15	15
Zinc	6	5		17	0	3	3	0	2	2
Redox	0	2	2	0	16	17	0	0	0	1
Electricity	10	2	2	2	1	0	2	4	16	3
To accept electron	1	1	2	0	11	11	0	0	0	0
To give up electron	0	2	3	0	10	12	0	0	1	0
Galvanic	5	8	1	3	0	2	7	1	1	10
Charge balance	0	0	0	0	0	1	12	0	1	0
Potential	3	4	3	3	3	7	2	2	5	2
KNO_3	1	0	1	0	0	0	11	0	0	0
Anion	4	4	2	4	3	6	5	3	1	4
Cation	4	4	3	3	5	5	5	3	1	4
Current	5	0	0	6	1	1	2	2	7	2
Insulator	1	0	0	0	0	0	0	0	9	0
Conducting wire	1	1	1	0	0	0	1	1	7	2
Half reaction	2	1	2	1	5	6	0	1	0	1

map, it is seen that this concept appears as a separate island, not included in the island where the existing relationships between concepts are established.

The Fig. 2 was generated solely based on participants' word associations that met the pre-established frequency thresholds. The fact that some core concepts—such as conductivity—appear

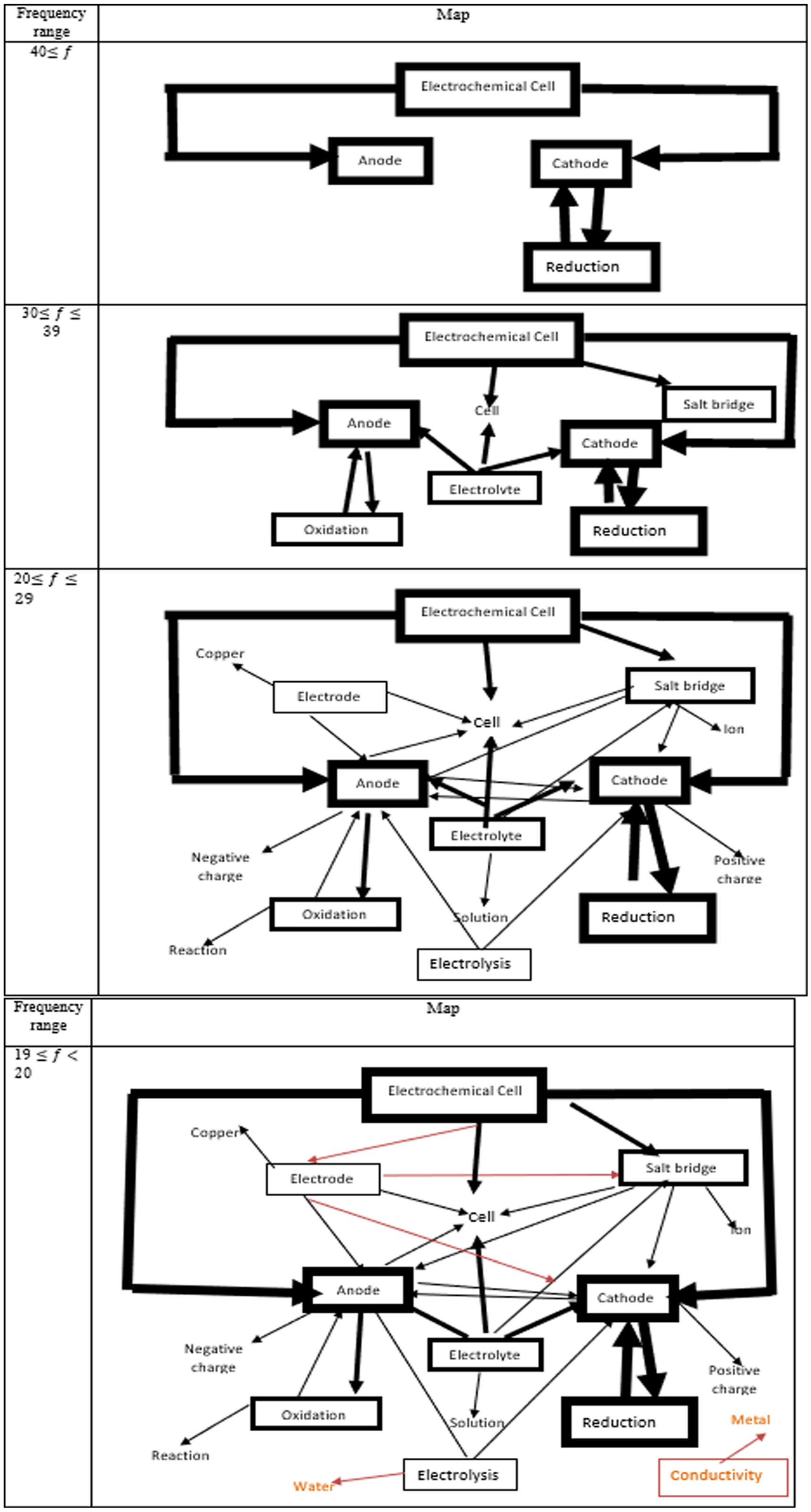


Fig. 2 PSCTs' group cognitive structure about electrochemistry.

isolated or that certain expected associative responses did not emerge in the map reflects limitations in the participants' conceptual articulations rather than analytical omissions. These patterns suggest that some concepts may not have been sufficiently internalized or consistently verbalized by the participants, which in turn shaped the structure and density of the resulting cognitive map.

Findings about the level of overall understanding of electrochemical concepts and the correct answer rates for questions in the test

The third research question first investigated the overall level of PSCTs' comprehension of electrochemical concepts and their correct response rates on the electrochemistry test. Table 6 provides the PSCTs' comprehensive understanding of electrochemistry concepts.

Reviewing Table 6 indicates that the mean score of the PSCTs is 7.10 out of 18 points. This situation shows that the average success score of the students is below 50%. The findings showing the frequency and percentage of correct and incorrect responses to each question are presented in Table 7.

Table 7 shows that the correct answer rates vary between 7.5% and 66.3%. Detailed explanations regarding the PSCTs' understanding of these questions were presented in the fourth research question below.

Table 6 Statistics of the ECT

Statistics	
Number of cases	80
Number of items	18
Variance	5.49
Mean	7.10
St. Deviation	2.34

Table 7 Percentage and frequencies of PSCTs who answered each question in the ECT

Question number	Correct		Wrong		Empty	
	Frequency	Percent	Frequency	Percent	Frequency	Percent
1	6	7.5	74	92.5	0	0
2	12	15.0	68	85.0	0	0
3	16	20.0	62	77.5	2	2.5
4	37	46.2	43	53.8	0	0
5	25	31.2	55	68.8	0	0
6	22	27.5	58	72.5	0	0
7	23	28.8	56	70.0	1	1.2
8	45	56.3	34	42.5	1	1.2
9	45	56.3	34	42.5	1	1.2
10	31	38.8	47	58.7	2	2.5
11	48	60.0	31	38.8	1	1.2
12	32	40.0	47	58.8	1	1.2
13	53	66.3	26	32.5	1	1.2
14	50	62.5	29	36.3	1	1.2
15	21	26.3	58	72.5	1	1.2
16	41	51.3	38	47.5	1	1.2
17	40	50.0	39	48.8	1	1.2
18	21	26.3	58	72.5	1	1.2

Findings about consistency in the PSCTs' understanding of electrochemical concepts related to the five conceptual categories and alternative conceptions

The fourth research question focused on assessing the consistency in the PSCTs' comprehension of electrochemical concepts across the five conceptual categories. Table 8 presents the calculated percentages and frequencies of PSCTs who correctly answered all questions within each conceptual category.

Table 8 reveals that the level of consistency across the groups ranged from 1.2% to 26.2%, with the highest consistency observed in the conceptual category "the poles in voltaic cells". Conversely, the lowest consistency rate was found in the category "Movement of ions in voltaic cells".

The second part of this research question examined whether the PSCTs held alternative conceptions within each conceptual group. To address this, Table 9 was constructed by calculating the frequency and percentage values for the response options of each question and is presented below. Then, using the data in Table 9, ACS values were calculated for the option reflecting a dominant alternative conception in each question. In addition, if there was another option that, while not directly representing

Table 8 The PSCTs who provided correct responses to all items within each of the five conceptual categories

The conceptual groups	*f*	%
Reactions occurring during electrolysis	2	2.5
Differences between electrolytic and voltaic cells	3	3.8
Movement of ions in voltaic cells	1	1.2
Poles in voltaic cells	21	26.2
Voltaic cell reactions	5	6.2

Table 9 Frequency and percentage of selection of options by PSCTs for questions in each conceptual groups

Conceptual groups	Question number	Options: a		b		c		d		Empty	
		f	%	*f*	%	*f*	%	*f*	%	*f*	%
1	1	11	13.8	**6**	**7.5**	63	78.8	—	—	0	0
	2	9	11.2	36	45.0	**12**	**15.0**	23	28.8	0	0
	17	**40**	**50.0**	39	48.8	—	—	—	—	1	1.2
2	3	24	30.0	29	36.2	**16**	**20.0**	9	11.2	2	2.5
	4	30	37.5	8	10.0	**37**	**46.2**	5	6.2	0	0
	9	4	5.0	20	25.0	**45**	**56.2**	10	12.0	1	1.2
	18	23	28.8	29	36.2	**21**	**26.3**	6	7.5	1	1.2
3	5	**25**	**31.2**	39	48.8	6	7.5	10	12.5	0	0
	7	**23**	**28.8**	17	21.2	24	30.0	15	18.2	1	1.2
	8	10	12.5	6	7.5	18	22.5	**45**	**56.2**	1	1.2
	10	25	31.2	10	12.5	**31**	**38.8**	12	15.0	2	2.5
4	11	25	31.2	**48**	**60.0**	4	5.0	2	2.5	1	1.2
	12	19	23.8	**32**	**40.0**	6	7.5	22	27.5	1	1.2
	13	3	3.8	**53**	**66.2**	21	26.2	2	2.5	1	1.2
	14	**50**	**62.5**	29	36.3	—	—	—	—	1	1.2
5	6	18	22.5	3	3.8	**22**	**27.5**	37	46.2	0	0
	15	23	28.8	2	2.5	**21**	**26.3**	33	41.2	1	1.2
	16	20	25.1	9	11.2	9	11.2	**41**	**51.3**	1	1.2

Table 10 ACS values for the alternative conception options of the questions in each conceptual group

Conceptual groups	Question number	Option	ACS
1	1	c	0.85
	2	b	0.53
		d	0.34
	17	a	0.98
2	3	b	0.45
		a	0,38
	4	a	0.70
	9	b	0.58
	18	a	0.39
		b	0.49
3	5	b	0.71
	7	c	0.42
		b	0.30
		d	0.26
	8	c	0.51
	10	a	0.51
		b	0.20
4	11	a	0.78
	12	a	0.40
		d	0.46
	13	c	0.78
	14	b	0.97
5	6	d	0.64
	15	d	0.56
		a	0.40
	16	a	0.52

an alternative conception, partially included such a conception or reinforced the expression found in the alternative conception option, its ACS value was also calculated. Based on these data, Table 10 was constructed.

The findings of the alternative conceptions belonging to each conceptual group (CG) are presented below.

CG1: reactions occurring during electrolysis. To find answers to this conceptual group, contains three questions (questions 1, 2, and 17) as seen from Table 9. Questions 1 and 2 examine whether the PSCTs knew exactly what happened during electrolysis, and it was also investigated whether they thought that the ionization of strong electrolytes was related to electrolysis. The percentage of the PSCTs who answered question 1 correctly is 7.5%. The correct answer to this question is option b, ''H_2 is formed at the negative terminal, Cl_2 at the positive terminal.'' The statement ''HCl is decomposed by electrolysis into H^+ and Cl^- ions,'' in option a, was selected by 13.8% of the PSCTs, while a significant proportion of the PSCTs (78.8%) selected option c. Option c indicates that both statements in options a and b are true. The statement ''HCl is decomposed by electrolysis into H^+ and Cl^- ions,'' in options a and c, suggests either a lack of understanding regarding the strong electrolytic nature of hydrochloric acid or the presence of an alternative conception. Specifically, these students may misconstrue the process of electrolysis as the decomposition of hydrochloric acid directly into its constituent ions. ACS value of this option is 0.85 in Table 10. A comparable alternative conception was also evident in the responses to question 2. Only 15.0% of accurate responses to question 2 were recorded, indicating a significant challenge in comprehending the underlying concept. It is seen from the table that 45.0% of the PCTs chose option ''b'' in this question. Option (b) presents the statement: ''HCl is decomposed by electrolysis into H^+ and Cl^- ions. At the negative terminal, two H^+ ions combine to form H_2.'' Meanwhile, 28.8% of the participants also selected option (d), which states: ''HCl is decomposed by electrolysis into H^+ and Cl^- ions (ACS value of option d is 0.34). At the negative terminal, two H^+ ions accept one electron each to form H_2.'' Both responses highlight a persistent conceptual challenge among the participants, particularly their misunderstanding of hydrochloric acid as a strong electrolyte. In question 17, participants were provided with the reactions occurring at the cathode and anode during electrolysis. They were questioned to identify these electrodes in the electrolytic cell using the provided reactions. While 50.0% of the participants successfully answered this question, the remaining 50.0% failed to correctly determine the cathode, indicating a gap in their ability to connect reaction processes to electrode identification. ACS value of this option is 0.85 in Table 9.

CG2: differences between electrolytic and voltaic cells. There are four questions (3, 4, 9, and 18) in this GC. In Question 3, the assessment focused on students' conception of electric current in aqueous solutions within electrolytic cells, revealing that only 20.0% provided the correct response. The desired answer was: *''Positively and negatively charged ions flow through the solution in opposite directions.''* Despite this, 36.2% of the students selected option (b), stating: *''Ions accept electrons at one electrode and carry them through the solution to the other electrode,''* while 30.0% chose option (a): *''Electrons flow through the solution from one electrode to the other.''* It is seen from the Table 9 that the ACS values of options b and a are 0.45 and 0.38 respectively. These findings demonstrate that many PSCTs misunderstand the nature of solution conductivity and mistakenly equate it with the mechanisms underlying metallic conductivity.

Question 4 addresses the flow of electrons in a voltaic cell, and as shown in Table 8, 46.2% of the PSCTs correctly selected option (c) as their answer. However, 37.5% of the participants chose option (a), which states: ''From the anode to the cathode through the salt bridge.'' The ACS value of option c is 0.70. This selection indicates that these PSCTs hold an alternative conception, mistakenly believing that the electron flow in a voltaic cell occurs through the salt bridge, rather than through the external circuit connecting the anode and cathode.

Question 9 investigated PSCTs' alternative conceptions regarding the distinction between galvanic and electrolytic cells, specifically focusing on the occurrence of spontaneous reactions in voltaic and electrolytic cells. In this question, 56.2% of the participants selected option (c) correctly, indicating that more than half of the PSCTs understand the fundamental difference between the two types of cells: electrical energy is converted to chemical energy in an electrolytic cell, whereas chemical energy is converted to electrical energy in a voltaic cell. However, it is notable that 25.0% of the participants selected option (b), which presents the exact opposite concept of option (c). The ACS value of option b is 0.58.

Question 18 examines the distinction between galvanic and electrolytic cells, focusing on the movement of ions driven by the electric field between the electrodes. Additionally, the question investigates whether PSCTs can correctly identify the flow of electrons within the solution. The correct response for this question (option c), chosen by 26.3% of participants, describes the movement of positively and negatively charged ions through the solution in opposite directions in an electrolytic cell. In contrast, 28.8% of the PSCTs selected option (a) that reflects an alternative conception, stating that electrons flow through the solution from one electrode to the other. Furthermore, 36.2% of participants chose option (b) that incorrectly suggests that Cu^{2+} ions accept electrons at one electrode and carry them through the solution to the other electrode. It is seen from the Table 9 that the ACS values of options a and b are 0.39 and 0.49 respectively. These responses indicate that many PSCTs are unable to differentiate between the two types of cells based on the direction of ion flow. It also highlights an alternative conception, where students believe that ions are responsible for electron transport through the solution in the cell.

CG3: movement of ions in voltaic cells. The understanding of ion movement in maintaining charge balance within voltaic cells was explored through questions 5, 7, 8, and 10, focusing on the PSCTs' comprehension and potential alternative conceptions. Question 5 specifically examines the extent to which PSCTs understand ion movement in the salt bridge during the operation of the voltaic cell, as well as whether they hold any alternative conceptions. 31.2% of the PSCTs correctly selected option (a). This option states that cations in the salt bridge move toward the cathode, while anions move toward the anode. Upon reviewing Table 8, it is evident that 48.8% of the PSCTs chose option (b), which presents the exact opposite of this concept. This suggests a significant alternative conception regarding the direction of ion movement in the salt bridge during the cell's operation and its ACS value is 0.71.

Question 7 examined the extent to which PSCTs understood that the substance filling the salt bridge is a strong electrolyte and does not participate in the cell reaction. In this question, 28.8% of the PSCTs answered correctly. Meanwhile, 30.0% selected option (c), which indicated that while the substance in the salt bridge is not involved in the cell reaction, these PSCTs mistakenly assumed it to be a weak electrolyte. Additionally, 21.2% of PSCTs who chose option (b) believed that the electrolyte in the salt bridge is part of the cell reaction, even though they correctly identified it as a strong electrolyte. Finally, 18.2% of PSCTs selected option (d), which suggests they thought the salt bridge contained a weak electrolyte that participates in the cell reaction. The ACS values of options c, b and d are 0.42, 0.30 and 0.26 respectively.

Question 8 explored PSCTs' understanding of how electroneutrality is maintained in each of the half-cells through the movement of ions. It was found that 56.2% of the PSCTs believed that the total electric charges of cations and anions in the two half-cells are always equal. In contrast, 22.5% of the PSCTs selected an option (c) that suggested the numbers of cations and anions in the two half-cells are always identical. This finding indicates that these PSCTs mistake the equality of ion numbers for the balance of charge. The ACS value of option *c* is 0.51.

Question 10 assessed how well students understood the movement of ions in a voltaic cell and its relation to charge balance, was revisited. Additionally, the question examined whether students had alternative conceptions regarding the movement of electrons in the solution and how charge balance is maintained. While 38.8% of PSCTs answered this question correctly, 31.2% selected option (a), and 12.5% chose option (b). The PSCTs who selected both options demonstrate an alternative conception, mistakenly believing that electrons travel between the half-cells through a porous disk within the solution. In this question, the expression provided in option a reflects an alternative conception. While the direction of the process is correctly identified, the belief that electrons, rather than ions, are responsible for the movement indicates the presence of an alternative conception among the students. Similarly, option b may also be considered an alternative conception, albeit to a lesser extent, as it includes the notion of "electrons passing through the solution," thereby reinforcing the idea presented in option *a*. As shown in Table 9, the ACS value for option a is 0.51, whereas for option b it is 0.20.

CG4: poles in voltaic cells. Questions (11, 12, 13, and 14) in this conceptual group were designed to assess the PSCTs' understanding and potential misconceptions regarding the identification of the anode and cathode in voltaic cells. The fourth conceptual group examines students' ability to accurately distinguish between the cathode and anode in galvanic cells, based on the oxidation and reduction reactions, the charge of the cell poles, and the types of ions moving at the electrodes. In question 11, 60.0% of PSCTs gave the correct answer by choosing option (b). These students recognized that the cathode is the electrode at which reduction occurs, where positively charged ions gain electrons, and it is the electrode with a positive charge in the cell. The second most frequently selected option was (a), chosen by 31.2% of PSCTs. While these students correctly identified the cathode as the site where positive ions are reduced by accepting electrons, they mistakenly identified the cathode as the electrode with a negative charge in the cell. The ACS value of option b is 0.78.

According to Table 8, 40.0% of PSCTs selected the correct option (b) for question 12. These students understand that the cathode is the electrode to which positively charged ions migrate, and they correctly identified it as the positive electrode of the cell. Conversely, 23.8% of PSCTs selected option (a), which stated that the cathode is the electrode where positive ions flow. However, this option incorrectly described the cathode as the negative pole of the cell. 27.5% of PSCTs selected option (d), which state that the cathode is the electrode where positive ions flow away. Although the PSCTs who selected this option correctly identified it as the positive pole of the cell, they appear to hold the alternative conception that oxidation occurs at this electrode. The ACS values of options a and d are 0.40 and 0.46 respectively.

In question 13 and 14, this time, PSCTs' understanding of the anode and whether they made similar mistakes were investigated. In question 13, it was determined that 66.2% of PSCTs chose the correct option (b), and thus they thought that the anode was the electrode where the oxidation reaction took place and had a negative charge, while the cathode was the electrode where the reduction reaction occurred and had a positive charge. Although 26.2% of PSCTs who chose option c knew the reduction and oxidation events in the anode and cathode correctly, they thought that the anode and cathode had the opposite charges. The ACS value of options c is 0.78. In Q14, they were directly asked which electrode was negative in the given voltaic cell, and 62.5% of PSCTs were able to answer this question correctly. 36.3% of PSCTs think that the negative terminal is the copper electrode and the ACS value of this options is 0.97.

CG5: voltaic cell reactions. The questions in this conceptual group are 6, 15 and 16. The understanding levels of whether reduction and oxidation reactions occur simultaneously, where the chemical reaction occurs while the voltaic cell is operating, and whether inert electrodes do not take part in the cell reaction while the voltaic cell is operating were investigated. It is seen that the percentage of PSCTs who chose the correct option (c) in question 6 is 27.5%. PSCTs who chose option (d) in this question are 46.2% and it has been identified that an alternative conception exists, suggesting that oxidation and reduction reactions occur independently within the half-cells of a voltaic cell. The ACS value of option d is 0.64. Option a was chosen by 22.5% of PSCTs. These PSCTs show that although they know that oxidation and reduction reactions occur in the voltaic cell half-cell, they do not know that these reactions occur simultaneously. This option does not directly indicate an alternative concept but can be evaluated as a lack of knowledge.

Only 26.3% of the PSCTs correctly answered question 15, which inquiries about the location of the chemical reaction in a functioning voltaic cell. This indicates that these individuals understand that the chemical reaction takes place on the surface of the electrodes during the operation of a voltaic cell. The majority of PSCTs selected option (d) for this question, with 41.2% demonstrating an alternative conception that the chemical reaction in a functioning voltaic cell occurs both within the electrolyte solution and inside the electrode. The ACS value of option d is 0.56. It was also determined that 28.8% of PSCTs thought that the chemical reaction occurred in the electrolyte solution while the voltaic cell was operating. The ACS value of option a is 0.40.

In response to question 16, which addressed the role of an inert electrode, 51.3% of PSCTs answered correctly, demonstrating an understanding that the inert electrode does not participate in the cell reaction during the operation of a voltaic cell. Conversely, 25.1% selected an incorrect option (a), revealing an alternative conception that the inert electrode actively participates in the cell reaction and contributes to the formation of an insoluble substance in the electrolyte solution. The ACS value of option a is 0.52.

Findings regarding the comparison of the results obtained from the ECT and WAT according to the conceptual categories

The fifth research question focused on the extent to which the findings obtained from the ECT overlap with the WAT's concerning pattern and how they can support these findings, particularly about the five conceptual categories of electrochemistry. The findings obtained for this purpose are given in Table 11.

When Table 11 is examined, in the category of *reactions that occur during electrolysis*, the WAT data show that the concept of ''electrolysis'' has weak semantic ties with key concepts such as ''electrolyte'' and ''redox''. This situation can be associated with the alternative conceptions and low correct response rates observed in the ECT. In the category of *differences between electrolytic and voltanic cells*, both instruments reveal that participants have difficulty with conductivity and electron flow. The WAT results showed that the concepts of ''salt bridge'' and ''conductivity'' are associated with low frequency associations. In the category of *ion movement in voltaic cells*, scattered and disconnected relationships between concepts are also observed in the WAT data. This supports the persistent alternative conceptions regarding ion movement and charge balance detected in the ECT findings. In contrast, a stronger conceptual structure is observed in both tests in the category of *poles in voltaic cells*. The strong semantic representation of anode-oxidation and cathode-reduction relationships in WAT may be associated with high success rates in ECT. Finally, in the *voltaic cell reactions* category, both tools indicate participants' conceptual deficiencies. No meaningful associations were obtained in WAT for concepts such

Table 11 The comparison of the findings of ECT and WAT patterns according to the conceptual categories

Conceptual category	ECT findings	WAT patterns
Reactions during electrolysis	Alternative conception: electrolyte ionizes during electrolysis. Poor identification of electrodes. No redox association. Correct answers very low (Q1: 7.5%, Q2: 15%).	Weak semantic links between 'electrolysis' and 'electrolyte' or redox concepts. Mostly associated with water.
Differences: electrolytic *vs.* voltaic	Alternative conception: electrons flow through solution/salt bridge. Weak understanding of conductivity. Correct answers vary (Q3: 20%, Q4: 46.2%).	'Conductivity' and 'salt bridge' appear with low frequency. Not connected to electrons or electroneutrality.
Ion movement in voltaic cells	Alternative conception about direction of ion movement in salt bridge. Confusion about electroneutrality (Q5: 31.2%, Q8: 22.5% correct).	No strong links between 'salt bridge' and ion movement. 'Charge balance' rarely activated.
Poles in voltaic cells	Good recognition of anode/cathode redox roles. Sign confusion persists (Q11: 60%, Q13: 66.2%, Q14: 62.5%).	Strong links: anode-oxidation, cathode-reduction. 'Positive/negative charge' weakly connected.
Voltaic cell reactions	Alternative conception: redox occurs separately. Confusion about inert electrodes. Mixed success rates (Q6: 27.5%, Q15: 26.3%).	'Electrode' linked to metals like Cu/Zn, no mention of 'inert'. No semantic link to redox or reactions.

as "inert electrode" and "reaction mechanism." This situation seems to support the confusion about the chemical role of electrodes observed in ECT findings.

Conclusions and discussion

In this study carried out several key analyses. First, the findings obtained from two different assessment tools, the ECT and the WAT, were compared to evaluate the degree of overlap between them and to explore potential relationships between PSCTs' conceptual understanding of electrochemistry and their underlying cognitive structures. Second, PSCTs' cognitive structure patterns were examined through cognitive mapping techniques and it was evaluated to what extent some stimulus concepts that they found close to each other in semantic memory could be included in the context of the knowledge structure pattern. Lastly, the data obtained from PSCTs were compared with those of upper secondary students who had previously completed the same instruments, thereby enabling a cross-level comparison of conceptual difficulties and contributing to more grounded pedagogical implications for both chemistry teacher training and curriculum development.

In the first research question the semantic relatedness of stimulus concepts related to electrochemistry within the semantic memory of the PSCTs were investigated. To answer this question, the RC values calculated and the semantic relatedness map was constructed by using RC values. When the RC values were examined, it was seen that the semantic relationship values between the stimulus concept pairs were above 0.5 in most of them and were quite high. The highest related key concepts were seen to be between electrolyte and electrochemical cell (0.92), while it was determined that there were three concept pairs with RC values below 0.5. These were cathode and reduction (0.45), anode and oxidation (0.48), and electrolyte and electrode (0.45).

Semantic memory organizes information according to semantic similarity. The brain stores concepts with similar meanings more closely. Since the RC value obtained with WAT is a direct measure of the number of words students give to two stimulus words, it can also be an indicator that a higher RC value can be obtained with a small but similar number of responses for two stimulus words (Bahar *et al.*, 1999). In addition, although these values are high or low, they show how connected the mental representations of the concepts are, these connections may not always mean that they are conceptually correctly understood. Especially if concepts belonging to different ontological categories are represented with a high RC value in students' mental networks, this may indicate ontological confusion (Chi, 2005). Students may tend to use these concepts interchangeably, which causes learning difficulties. On the other hand, if the concepts are in the same ontological category (*e.g.* both are processes or substances) and are associated with a high RC value, this relationship may be more meaningful and conceptually consistent. For this reason, especially in fields such as science, when interpreting RC values, not only the numerical closeness of the RC value and the ontological categories to which the concepts belong should be taken into consideration (Slotta and Chi, 2006). Especially when it comes to semantically related chemistry concepts as in this study. When we interpret the RC values obtained in the study from this perspective, for example, the fact that the concepts of electrolysis and electrochemical cell are so semantically close with a high RC value of 0.84 can be associated with electrolysis being a type of electrochemical cell. Because the similar components that will be the answer to both are concepts such as anode, cathode, oxidation, reduction, electrolyte. On the other hand, although this situation explains semantic closeness, it does not have to be directly related to conceptual understanding, and as will be seen in the interpretation of the cognitive structure map below, these two concepts are appropriately associated in the cognitive structure through the common concepts anode and cathode, which enable them to be semantically similar, even though they are not directly related in the cognitive structure. Regarding cathode and reduction (RC = 0.45) and anode and oxidation (0.48), which have RC values below 0.5, the exact opposite of the electrochemical cell and electrolysis above is the case. Although their semantic closeness is below 0.5, they are directly related in the cognitive structure and even cathode and reduction are included in the cognitive structure map at the highest frequency value. The ontological categories of anode and cathode are matter and both are considered ontologically as physical entities. On the other hand, the ontological categories of reduction and oxidation concepts are processes and are events related to electron gain or loss. This difference in ontological categories can be interpreted as students' semantic memory not finding many relationships. On the other hand, oxidation in the anode and reduction in the cathode are extremely important in terms of conceptual understanding and these strong and direct relationships have taken their place in the cognitive structure as shown in the cognitive structure map.

In the second research question, the relationships between the stimulus concepts of electrochemistry and the response concepts related to these concepts in the group cognitive structures of PSCTs were investigated. For this purpose, the cognitive structure map was drawn using the frequency values obtained for the response concepts. When their cognitive structures were examined, it was determined that the highest relationship was between the stimulus concepts, the electrochemical cell and its components and that this relationship was established appropriately. It was concluded that the six stimulus concepts (electrochemical cell, salt bridge, electrode, anode, cathode, and electrolyte) that emerged in the high-frequency range were connected *via* the response concept "cell" and, the other three stimulus concepts (electrolysis, oxidation and reduction) linked them to form an island in the PSCTs' cognitive structure. It is quite logical that PSCTs strongly associate the cell and its components, and the cell is in the centre of this island. Gericke and Wahlberg (2013) emphasized that certain concepts hold a more central position, while others are relatively peripheral, reflecting the hierarchical organization of knowledge. In the mapped cognitive structure, the placement of the cell concept at the centre, surrounded by related concepts, can be interpreted as representing an appropriate hierarchical organization. In addition, the association of the concepts of electrolysis, oxidation and reduction together as an island can be interpreted as a correct association when viewed in terms of ontological categories. Because electrolysis is a dynamic transformation process in which a chemical reaction occurs with externally supplied electrical energy, this shows that its ontological category is process. Similarly, oxidation and reduction are chemical events whose ontological category is process. The observed distinction between the terms "cell" and "electrochemical cell" also reflects a meaningful cognitive differentiation made by PSCTs. While both terms refer to the same scientific phenomenon, PSCTs used "cell" in reference to physical objects encountered in daily life—such as household batteries—whereas "electrochemical cell" was more often used to describe textbook representations or laboratory setups. For this reason, the two terms were retained as separate nodes, providing insight into how PSCTs categorize concepts based on context and abstraction level. A similar rationale applies to the terms "solution" and "electrolyte," which were also preserved as distinct entries in the map. Although conceptually related, "solution" is a more general term encompassing both electrolytic and non-electrolytic media (*e.g.*, sugar solutions). The co-occurrence of both terms in participant responses suggests that some PSCTs were aware that the type of solution used in electrochemical systems must exhibit electrolytic conductivity. This separation allowed for the identification of conceptual nuances in students' mental representations.

An additional conclusion regarding the cognitive structure of PSCTs is that stimulus word "conductivity" emerged in a lower frequency range of the cognitive structure map and is not connected to the island where the cell concept is placed in the centre. This shows that conductivity is the concept that has the weakest relationship with the electrochemical cell and its components. Besides, the response concept that emerged for conductivity is only metal and this situation shows that the PSCTs thought of metallic conductivity rather than electrolytic conductivity as conductivity. This is particularly related to the fact that metallic conductivity is also covered more in physics courses and students are expected to relate the knowledge they acquire in physics courses to the teaching of conductivity in chemistry courses. In this context, Garnett and Treagust (1992a) argued that chemistry and physics are frequently taught as distinct disciplines. Consequently, they highlighted that student struggled to apply the concepts of electrical conductivity learned in physics to explain the flow of electrical current in an aqueous solution in chemistry.

The fact that "conductivity" appeared only in connection with "metal" and not with "electrolyte" indicates that PSCTs were primarily recalling metallic, rather than electrolytic, conduction. This limited linkage emerged solely from the frequency distribution of participant-generated associations and not from any researcher categorization. The peripheral and isolated placement of "conductivity" on the map reflects this pattern, further supporting the interpretation that ionic conduction was underrepresented in participants' cognitive structures. Moreover, the concepts of "voltaic cell" and "electrolytic cell" did not appear as distinct entities in the map, despite their theoretical importance in electrochemistry. This was not due to an oversight, but rather because these terms were mentioned only by a small number of participants and did not meet the minimum frequency threshold for inclusion in the final visualization. This absence suggests that many participants either did not conceptually distinguish between the two systems or lacked the terminology to do so—a limitation that is now explicitly addressed in the discussion. Similarly, the absence of "power source" in the cognitive structure is not the result of an analytical omission, but reflects the very limited frequency with which this concept was mentioned by participants. Despite its fundamental role in enabling electrolysis, "power source" did not reach the frequency criterion required for inclusion. This highlights a gap in how PSCTs conceptualize functional components within electrochemical systems and is also discussed in the revised manuscript as a notable finding.

After mapping the PSCTs' cognitive structures, the present study further investigated their level of understanding of electrochemistry topics and concepts in third and fourth research questions. For this purpose, the same ECT, which was previously used by Rahayu *et al.* (2011) to assess the achievement of Japanese and Indonesian students and by Nakiboğlu *et al.* (2024) to assess Turkish 12th grade and Indonesian students' achievements, was also used in this study to determine the achievements of PSCTs' concerning electrochemistry concepts. When the average success of PSCTs in the ECT is examined, it is determined that it is about 40%. When comparing this conclusion with the results of prior research on the ECT, it becomes evident that earlier studies consistently indicated a relatively limited understanding of electrochemistry concepts among students. This aligns with the broader trend of challenges in comprehending core principles within this domain, as reflected in the existing literature on the topic. The findings indicated that the performance of Indonesian, Japanese, and Turkish students across all these studies averaged approximately 40%. Students from each sample exhibited similar challenges, including numerous alternative conceptions regarding key electrochemical concepts such as electrolysis, electrical flow, voltaic cells, and electrode reactions. Furthermore, the students demonstrated limited consistency in their comprehension of the concepts across the five conceptual groups, suggesting significant gaps in their conceptual understanding of electrochemistry.

All of these results align with the findings of previous studies, reinforcing the consistency of the observed patterns (Allsop and George, 1982; Ogude and Bradley, 1994; Sanger and Greenbowe, 1997a, b; Lin *et al.*, 2002; Ahtee *et al.*, 2002; Özkaya *et al.*, 2003; Schmidt *et al.*, 2007; Ekiz *et al.*, 2011; Rahayu *et al.*, 2011; Akram *et al.*, 2014; Adu-Gyamfi *et al.*, 2015; Supasorn, 2015; Lu and Bi, 2016; Loh and Subramaniam, 2018a, b; Nakiboğlu and Nakiboğlu, 2018a, b; Rahayu *et al.*, 2022) indicating that electrochemistry topics and concepts are not easy for all level students even preservice chemistry students.

An important conclusion reached regarding the ECT findings of the study is that the PSCTs who received education according to the same program as the 12th-grade Turkish students in the test developed according to the secondary school chemistry program and who were later taught electrochemistry topics and concepts at the university level experienced similar problems related to electrochemistry. This situation can be attributed to the inherent complexity of electrochemistry topics and concepts, which often present significant challenges for students in terms of conceptual understanding. The electrochemistry topics and concepts are related to the macroscopic level of chemistry due to the events observed in laboratory studies on batteries and electrochemical cells (lighting of a bulb connected to the cell system, coating done by electrolysis, *etc.*). The explanation of the events taking place inside the cell takes place at the sub-microscopic level of chemistry. The similar symbols are used for both macroscopic and sub-microscopic levels. All these cause problems in understanding the electrochemistry topics and concepts of students. In fact, the current study's comparative analysis shows that PSCTs' success rates in most conceptual categories were close to those of the 12th-grade Turkish students, indicating that university-level instruction did not fully eliminate conceptual difficulties identified at the secondary level. The result obtained in this study regarding the similar success of PSCTs and upper-secondary school students in electrochemistry tests is also consistent with the findings of the study carried out by Rahayu *et al.* (2022). Rahayu *et al.* (2022) applied an electrochemistry concept test, which they developed based on the 12th-grade chemistry curriculum, to both 12th-grade students and pre-service chemistry teachers and compared overall success. They determined that although the general average tendency to understand electrochemistry concepts throughout university education showed some improvement, the average scores were relatively low. They even revealed that students' success was lower for both groups in items with high item difficulty levels. Thus, they concluded that the lack of understanding of electrochemical concepts is an ongoing challenge for high school and continuing university chemistry education.

In the final phase of the study, the focus was placed on the potential relationship between PSCTs' conceptual understanding and their cognitive structures, in line with the main aim of the research. Accordingly, ECT and WAT data were comparatively discussed. Based on the fifth research question, the extent to which WAT findings aligned with those from ECT—particularly across the five conceptual categories of electrochemistry—was examined, along with how these two data sources jointly illuminated the nature of students' knowledge structures. The aim of this comparison was not to establish strict validation between the instruments, but rather to identify points of convergence and divergence in PSCTs' conceptual understanding. This revealed that ECT and WAT findings were generally complementary and mutually supportive. In the following sections, each conceptual category is examined individually, and PSCTs' understanding of electrochemistry is discussed through an integrated approach that combines their concept test performance and cognitive structure data.

It was revealed that in the first conceptual group, reactions occurring during electrolysis, the PSCTs had an alternative conception that the electrolyte was ionized during electrolysis. In the study of Nakiboğlu *et al.* (2024) involving 12th-grade Turkish and Indonesian students, a similar conclusion was reached when the same electrochemistry test was applied to analyse reactions during electrolysis. The study indicated that nearly 70% of students from both countries held the misconception that the electrolyte undergoes decomposition to produce its ions during electrolysis. When compared to the 12th-grade Turkish students, PSCTs showed slightly lower frequency of correct answers in this category, suggesting that even after university-level exposure, misconceptions about electrolyte decomposition persist. This result corresponds with the findings of Rahayu *et al.* (2011), who applied the same test to Indonesian and Japanese students, as well as with various other studies in the literature (Ogude and Bradley, 1996; Sia *et al.*, 2012; Nakiboğlu *et al.*, 2024). In particular, Ogude and Bradley (1996) observed that students mistakenly thought the electric current fragmented the electrolyte into positive and negative ions. Upon examining the cognitive structure of the PSCTs, it was found that there is no connection between the concepts of electrolyte and electrolysis in their cognitive structure map. They only associate electrolysis with water in a weak way. This phenomenon may be attributed to the fact that during the teaching of electrolysis, the event is explained primarily as "water electrolysis" in textbooks. It was also concluded that they had problems determining the location of the anode and cathode in the electrolytic cell. The issue appears to stem from the fact that students did not focus on the electron transfer occurring at the electrodes when determining the charge of the cell pole. When the cognitive structure map was examined, in very low-frequency range, electrolysis is associated with the anode and cathode, but not with oxidation and reduction. These findings regarding the cognitive structure seem to support the findings obtained in the conceptual group, reactions occurring during electrolysis, in ECT. This alignment between the ECT and cognitive structure data is further reinforced by the WAT results, which revealed that 'electrolysis' was semantically connected primarily to 'water', while links to 'electrolyte' and 'redox' were notably absent. This semantic isolation supports the fragmented and poorly integrated conceptual understanding identified through the ECT. Moreover, these findings underscore that weak conceptual understanding may arise not only from low-frequency or missing associations but also from the presence of scientifically inaccurate yet semantically strong associations. Such alternative conceptions, when deeply rooted, can create a distorted but internally consistent structure that disrupts the integration of canonical scientific knowledge within the cognitive map. Therefore, both the absence of correct links and the presence of persistent misconceptions must be jointly considered when evaluating the quality of conceptual understanding.

The most important alternative conception determined in PSCTs in the second conceptual group, differences between electrolytic and voltaic cells, is "the electric current flows in the electrolyte solutions." Another prominent misconception in this group concerns the movement of electrons through the salt bridge in voltaic cells. These two alternative conceptions reflect a fundamental misunderstanding of conductivity and charge transport mechanisms. The comparison with 12th-grade Turkish students shows that PSCTs' performance in this category was only marginally higher, implying that core misunderstandings about current flow and electron movement remain largely unresolved despite advanced education. These results align with the findings reported in previous studies (Garnett and Treagust, 1992a, b; Sanger and Greenbowe, 1997a, b; Özkaya *et al.*, 2003; Schmidt *et al.*, 2007; Rahayu *et al.*, 2011; Sia *et al.*, 2012; Amponsah, 2020; Nakiboğlu *et al.*, 2024). When compared with cognitive structure data, it was previously noted that the concept of conductivity appeared with low frequency and was disconnected from other key concepts in the cognitive structure map. Similarly, WAT data revealed that 'conductivity' and 'salt bridge' were rarely activated and lacked semantic associations with 'electrons' or 'electroneutrality'. This overlap between ECT and WAT results suggests that PSCTs' difficulties in understanding physical charge transport are both conceptually and semantically rooted. Therefore, the cognitive structure analysis and the ECT findings appear to mutually reinforce one another in identifying the same areas of conceptual weakness.

It is also concluded that students encounter considerable difficulties in understanding the movement of ions within the salt bridge, particularly in relation to ion movement in the voltaic cell. Many PSCTs hold an alternative conception that anions in the salt bridge travel toward the cathode, while cations move toward the anode. Some also believe that ions either move in both directions or do not move at all. This alternative conception of ion transport in the salt bridge has been consistently documented in several studies and was also evident among 12th-grade Turkish students, thereby highlighting a common and persistent gap in conceptual clarity (Garnett and Treagust, 1992a, b; Sanger and Greenbowe, 1997a; Schmidt *et al.*, 2007; Rahayu *et al.*, 2011; Sia *et al.*, 2012; Nakiboğlu *et al.*, 2024). This indicates that PSCTs have an incomplete understanding of the role and function of the salt bridge in a voltaic cell or have problems understanding the principle of electroneutrality. When the cognitive structure of them is examined, it is seen that there is no connection between the salt bridge and electroneutrality in the frequency range in the last cell in the Fig. 2. On the other hand, when Table 9 containing the frequency values is examined, it is seen that there is a weak connection between the frequency value of the "12" salt bridge and the charge balance at low frequency. This may also be related to their ignorance of the properties of the electrolyte in the salt bridge. Especially the answer percentage in the first question was interpreted as there might be a problem in the PSCTs' knowledge about electrolytes. WAT findings echoed this: 'salt bridge' was rarely linked to ion movement or charge balance, showing weak conceptual integration.

The analysis revealed that the conceptual group related to the poles in voltaic cells is where students achieved the highest average success compared to other conceptual groups. The correct answer percentages in all questions of this category here are close to each other and are around 60%. When compared with the 12th-grade Turkish students, whose average success rate in this category was around 40%, the PSCTs demonstrated higher performance. The correct responses indicate that PSCTs have a strong ability to identify the types of reactions occurring at the anode and cathode in voltaic cells. An examination of their cognitive structures reveals that the concepts of anode and cathode are frequently and strongly associated with the electrochemical cell a high-frequency range. In addition, it has been determined that the concepts of reduction to the cathode and oxidation to the anode are correctly associated. This situation shows that the data obtained from ECT overlap with the data regarding the relationships in the cognitive structure. Consistently, WAT results also revealed that the concepts of anode and cathode were accurately associated with oxidation and reduction, respectively. However, semantic associations with the charge signs of these electrodes were found to be weak, highlighting that the confusion about electrode polarity still persists despite a solid understanding of redox processes.

On the other hand, in the cognitive structure, the response concept of "negative charge" was associated with the anode through its connection with the electrochemical cell, whereas the concept of "positive charge" was linked to the cathode, albeit at a relatively low frequency. This pattern indicates that students have difficulty determining the polarity of the electrodes. This issue is further evidenced by the frequent sign-related errors observed in their incorrect responses to the relevant items on the ECT. Although students often know which electrode is involved in oxidation or reduction, they still struggle to correctly assign the sign of the electrode. This may stem from their tendency to explain the phenomena by applying electrostatic reasoning rather than principles of charge balance. In such cases, students may reason that since the cathode is positively charged, the positively charged ions should move away from it (*i.e.*, the belief that like charges repel), or conversely, if positive ions move toward the cathode, then it must be negatively charged (*i.e.*, the belief that opposite charges attract). This suggests that students form conceptual associations not only on the basis of scientific accuracy but also through intuitive or flawed logical inferences. Indeed, the weak connections of 'positive/negative charge' in the cognitive structure map, along with the limited semantic associations found in the WAT data, further support the persistence of this confusion regarding electrode polarity.

The most significant alternative conception identified within the conceptual group of voltaic cell reactions was the belief that oxidation and reduction processes occur independently in the two half-cells. Approximately half of the PSCTs selected this incorrect response, while only a quarter identified the correct conceptual relationship. Similar findings have been reported by Nakiboğlu *et al.* (2024), suggesting the persistence of this alternative conception across diverse student populations (such as 12th-grade Turkish and Indonesian students). Another prevalent alternative conception in this group was the belief that the chemical reaction occurs within the electrolyte solution and inside the electrode during the operation of a voltaic cell, with approximately half of the participants selecting this option. Additionally, alternative conceptions regarding inert electrodes were observed: although half of the participants correctly identified that inert electrodes do not participate in the chemical reaction, one in four believed that these electrodes engage in the reaction and lead to the formation of insoluble substances in the electrolyte. When compared with the findings of the study by the Nakiboğlu *et al.* (2024), it was determined that they had similar alternative conceptions. The cognitive structure data complemented these findings by showing that participants associated the concept of "electrode" predominantly with metals such as copper and zinc, while the term "inert" did not appear among the response concepts. Likewise, no semantic associations emerged between 'electrode' and redox processes in the WAT data. This lack of conceptual linkage reflects not only gaps in canonical knowledge, but also suggests that persistent alternative conceptions—such as those concerning inert electrodes—may remain unarticulated in semantic networks, yet still actively shape students' reasoning. These results highlight that cognitive structures should be interpreted not only based on the presence or absence of scientifically accurate concepts, but also by considering which misconceptions may be implicitly embedded and structurally disruptive. Thus, both ECT and WAT results suggest that conceptual weaknesses in this group stem from both missing canonical associations and underlying alternative conceptions that are not explicitly verbalized in associative tasks.

Recommendations

In the study, the important alternative conceptions obtained from the achievement test of PSCTs and the low level of conception of PSCTs showed that some of the suggestions in this study should be made for the teaching of electrochemistry. In addition, the weak or unestablished associations that emerged in the cognitive structure also show that PSCTs have problems with structuring electrochemistry concepts in their minds. These issues stem not only from a lack of scientific connections but also from the presence of persistent alternative conceptions that can form semantically strong yet scientifically inaccurate knowledge frameworks. A weak grasp of fundamental concepts and principles, such as electrolyte, conductivity, and the principle of electroneutrality—core prerequisites for understanding the subject—hinders students' ability to learn other electrochemistry topics and to form accurate conceptual connections. For this reason, whether while teaching electrochemistry at the general chemistry level or taking a course on electrochemistry in other upper grades, students' prior knowledge should be reviewed in the first week of the course and their alternative conceptions, if any, should be corrected. For this purpose, the graphic organizers can be used for concept teaching. Nakiboğlu and Nakiboğlu (2021) conducted a study with pre-service chemistry teachers to explore the effectiveness of graphic organizers combined with interactive PowerPoint presentations in teaching electrochemistry concepts. The findings indicated that the participants believed such visual teaching tools could significantly improve students' understanding of electrochemistry topics while also increasing their engagement and motivation.

After teaching pre-requisite knowledge, it is also extremely important to include hands-on activities in the teaching of the electrochemistry subjects (Tsaparlis and Gorezi, 2005, 2007; Supasorn, 2015; Hunter *et al.*, 2019). In particular, the experiments involving these two cell setups should be conducted to solve the problem of differentiating galvanic and electrolytic cells. In cases where there is no opportunity to conduct experiments in a laboratory environment, "virtual laboratories" or computer animations can be used. Computer animations will also provide the opportunity to see the electrochemical events that occur especially at the sub-microscopic level. As mentioned in the findings section of the study, electrochemistry is also related to the three levels of chemistry (macro, sub-micro and symbolic). Several studies used computer animations in electrochemistry instruction (Sanger and Greenbowe, 2000; Yang *et al.*, 2003; Osman and Lee, 2014; Cole *et al.*, 2019). Chiu and Wu (2009) suggested that computer animations can enhance students' comprehension of chemical processes and concepts in electrochemistry by improving their ability to visualize submicroscopic phenomena. These animations provide dynamic representations that help bridge the gap between abstract theoretical concepts and their underlying molecular-level operations.

Loh and Subramaniam (2018a, b), in their study on students' knowledge structures regarding galvanic cells, highlighted the importance of directing students' focus toward the dynamic interactions of electrons and ions during the functioning of these cells. They emphasized that a comprehensive understanding of galvanic cells requires students to conceptualize the system as a whole. Additionally, they identified three essential components for effective learning: electron transfer during oxidation and reduction half-reactions, electron flow through metallic conductors, and ion migration within the solution. We agree with this suggestion for teaching the galvanic cell. Furthermore, it is crucial to ensure that students develop a similar understanding of the electrolytic cell and recognize the key differences between the two types of cells. This can be effectively achieved through the use of visual aids, animations, or hands-on experiments in the chemistry laboratory.

Zhang *et al.* (2021) emphasized that examining students' cognitive structures in a specific discipline involves studying the cognitive factors, perspectives, and patterns that shape their knowledge. Their research revealed that students' knowledge structure, cognitive perspective, and cognitive patterns were all linked to their chemistry performance, with cognitive perspective emerging as the most influential factor. They concluded that higher-achieving students tend to have a well-organized and systematic knowledge structure, whereas lower-achieving students often exhibit isolated or limited knowledge points. Given that similar results were obtained in this study, it is recommended that achievement tests and cognitive structure mapping techniques, which complement each other, be used together for evaluating student performance in chemistry. These methods should be incorporated at various stages of the teaching process to provide a more comprehensive assessment of students' understanding.

Moreover, teacher training programs should be enriched with activities that help preservice chemistry teachers identify and reflect on their own alternative conceptions. Semantic mapping activities combined with guided conceptual critique tasks can reveal deeply entrenched but scientifically inaccurate associations in their cognitive structures. Such metacognitive practices can enhance awareness and support meaningful conceptual change.

A suggestion for the study can be made to teachers and studies conducted to collect data with WAT and both mapping cognitive structures and look for the semantic relatedness of stimulus concepts in semantic memory. As previously stated by Bahar *et al.* (1999), semantic relatedness calculation is laborious and time-consuming, and teachers do not need to deal with semantic memory in classroom assessments in science fields. Instead, mapping cognitive structures, which is much easier and informative for conceptual understanding, can be used. Similar to the findings of this study, differences were observed between the relationships between the semantic memory map and the cognitive structure map in the study conducted by Nakiboğlu (2008) on atoms. As explained in the commentary of the first research question, although there are different reasons for this, one of the important reasons is that the concepts are in different or similar ontological categories. For this reason, it can be suggested that such a comparison be made in such studies conducted in the field of science, and that researchers working on ontological categories in particular should conduct different studies to see the reproducibility of this important result found here and reach more advanced results.

Limitation of the study

In this study, cognitive structure maps were obtained on behalf of the group. The findings acquired as a result of the conceptual test also belong to the group. However, since both data sets are not in a way that will allow for a statistical comparison, it is not possible to make a comparison in this way. So, a qualitative comparison at the conceptual category level was conducted. It can be considered as a limitation of the study in that the study data do not allow for a one-to-one comparison of cognitive structure and conceptual understanding. In addition, cognitive structure maps based on WAT may include semantically strong but scientifically incorrect associations, which limits the interpretation of conceptual understanding purely based on network structure. On the other hand, when previous studies on group cognitive structures obtained using WAT for science subjects (Bahar *et al.*, 1999; Nakiboğlu, 2008, 2023; 2024; Gulacar *et al.*, 2022) are examined, it has been revealed that WAT results can provide appropriate perspectives on the knowledge structure of students. Therefore, this study should be taken into consideration in terms of providing a perspective to the chemistry education researchers by combining two different types of data. To reveal such relationships in more depth, it is possible to collect data through bilateral interviews and analyse them in different ways. However, considering the time-consuming nature of bilateral interviews and the long duration of analyses, the path followed in the study can provide researchers with a starting point. On the other hand, future research could incorporate small-scale interviews or open-ended responses during the validation process to further ensure that multiple-choice formats, such as the ECT, are not unintentionally leading participants' answers.

Author contributions

C. N. conceptualised and designed the methodology. Both authors formally validated all data. C. N. analysed and visualised all data. N. N. interpreted ECQ findings. Both authors contributed to the original draft preparation and reviewing and editing the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this study were collected from human participants and are not publicly available due to ethical considerations and participant confidentiality. Access to the data can be provided upon reasonable request to the corresponding author, contingent on approval from the relevant ethics committee and in compliance with data protection regulations.

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