The Periodic Table and The Learning of Chemistry: Possibilities of Integrating Robotics and Concept-Based Approaches in Teaching

Thabo Mhlongo[1], Thomas Dipogiso Sedumed[2]
Tshwane University of Technology, South Africa
e-mail: t.man907@hotmail.com[1], sedumeditdt@tut.ac.za[2]

Abstract

In this study, the authors investigate the potential of integrating robotics technology and concept-based teaching approaches to enhance the learning of abstract Chemistry concepts, focusing on the periodic table as both subject matter and tool. Utilizing a quasi-experimental design, the research employs descriptive quantitative and qualitative methods for data collection, including pre- and post-test experimental designs. Results suggest that combining robotics with concept-based teaching improves learners' deep understanding of chemistry concepts. The study highlights the promising benefits of integrating robotics technology and a concept-based approach for teaching chemistry, emphasizing the need for further research in this area.

Keywords: Robotics, Concept-based approach, Periodic table, Deep meaningful learning, Chemistry concepts.

INTRODUCTION

The periodic table is a central concept and/or a system in chemistry teaching as it provides a framework for organizing and understanding the properties and behaviour of matter at the elemental and atomic levels (Scerri, 2019; Cao, Vernon, Schwarz, & Li, 2021). However, despite its importance, the periodic table remains a challenging topic for many learners to comprehend and often requires hours of memorization without fostering deep conceptual understanding (Mudau, & Nkopodi, 2015; Traver et al., 2021; Mhlongo & Sedumedi, 2023). In an attempt to address this challenge, the researchers have thought of a range of innovative teaching approaches that would enhance learners' engagement and conceptual understanding of abstract Chemistry concepts through the understanding of the periodic table.

One of the innovations considered is to integrate robotics technology into chemistry teaching. Integrating robotics technology in teaching would involve the design, construction, and use of robots to perform various tasks (David, 2018). This integration would involve robotics technology to teach abstract or difficult concepts because it enables learners to interact with machines that represent the concept in a tangible and visual way (Lim, Bahri & Goh, 2020). For example, in the context of this study, robotics complemented and enhanced the teaching of chemistry concepts of the periodic table or its system. The 3D-printed models designed by the researcher and robots that can move and manipulate the elements during the learning process were used. This integration provides an interactive and engaging learning experience through which learners explore, experiment, and solve real-life problems related to the concept they are studying (Lim, Bahri & Goh, 2020).

Thus, robotics technology may help simplify the comprehension of the periodic table by providing learners with interactive and visual tools that represent the elements and their properties (Morales-Menendez, Garcia-Méndez & Zizumbo-Villarreal, 2016). With the use of robotics technology, learners can manipulate and rearrange the elements on a 3D-printed periodic table, observe the interaction of elements, and visualize how they form molecules (Turchi, Aleotti & Caselli, 2020; Ding et al., 2018; Liu, Golonka & Curin, 2019). Additionally, robots have the potential to assist learners in performing experiments to demonstrate the properties of different elements and their reactions, giving a hands-on experience with the periodic table. These interactive and visual aids enable learners to grasp the periodic table more effectively, enhancing their comprehension of this abstract and complex concept (Lim, Bahri & Goh, 2020).

Furthermore, there is growing evidence that integrating robotics in chemistry teaching and learning and in education generally can lead to greater learner engagement and improved learning outcomes [e.g. Verner & Revzin, 2017; Sánchez, Martínez, & González, 2019]. For example, Alimisis (2012) found that using robotics in chemistry learning improved learners' understanding of chemical concepts and enhanced their motivation to learn science. Similarly, Alimisis (2012) observed that incorporating robotics technology in a physics course resulted in greater learner engagement and conceptual learning gains. Several studies (Herald, 2019; Verner & Revzin, 2017; Sánchez, Martínez, & González, 2019) have examined the effectiveness of robotics technology in teaching the periodic table specifically. For example, Herald (2019) employed LEGO Mindstorms robotics to teach the periodic table and found that this approach facilitated learners' understanding of the periodic trends and enhanced their problem-solving skills.

In their study, Mhlongo and Sedumedi (2023) found that the comprehension level of the periodic table has a significant impact on how learners perceive chemistry concepts. Those who grasp the fundamental concepts of the periodic table demonstrate a better understanding of chemistry, while those who struggle with the periodic table struggle with other chemistry concepts. Another critical factor in enhancing learners' engagement and conceptual understanding of the periodic table is the use of concept-based approaches to teaching. Concept-based teaching emphasizes a deep understanding of underlying concepts and patterns, helping learners connect new information to existing knowledge (Wiggins & McTighe, 2011). Concept-based teaching refers to an instructional approach that emphasizes the teaching of broad, transferable ideas or concepts that transcend specific content areas and can be applied to new and diverse situations. It involves teaching learners how to think critically, make connections between related ideas, and transfer their knowledge to real-world situations (Lin & Lai, 2018). Concept-based teaching aligns well with robotics technology, as it fosters opportunities to visualize and manipulate abstract concepts such as those presented in the periodic table.

Integrating has emerged as a promising approach for enhancing learners' engagement, conceptual understanding, and problem-solving skills (Kara & Bayırtepe, 2021). Integrating robotics technology in chemistry education means incorporating robotics technology as a tool or method of teaching within the chemistry subject, rather than as a stand-alone subject. It involves utilizing robotics technology to enhance learners' understanding of chemistry concepts by providing them with interactive and engaging learning experiences. As a method of teaching chemistry, the use of robotics technology in chemistry education can take various forms, such as displaying 3D-printed models of atoms and molecules, using robots to perform experiments and reactions, or programming robots to simulate chemical processes. The benefits are particularly notable when incorporating robotics into a concept-based approach to teaching, which emphasizes understanding abstract concepts and aligns well with hands-on and interactive learning experiences (Valko & Osadchyi, 2021). While challenges related to access to technology in developing countries remain, the potential benefits of integrating robotics in chemistry teaching warrant further research and exploration.

There is a significant gap in the literature regarding the integration of robotics to teach Chemistry, especially about the Periodic Table. The gap in the literature mentioned refers to the lack of research that specifically explores the use of robotics technology in teaching chemistry and the understanding of the Periodic Table in chemistry education. While there may be studies on the use of robotics technology in chemistry education, there may be limited research on its application to teaching chemistry concepts, Periodic Table specifically, which could lead to a gap in knowledge about its potential benefits or limitations for enhancing learners' understanding of these concepts.

Although some studies like the ones mentioned have explored the use of robots in teaching Chemistry, the literature lacks studies on the effectiveness of using robotics as a tool to teach specific chemistry topics and how learners' learning outcomes relate to the use of robotics. Hence, the paring of robotics as a research tool with a concept-based approach for teaching and learning. A concept-based approach means focusing on teaching chemistry with a focus on concepts instead of just rote memorization of facts or procedures. In this paper, a concept-based approach is emphasized in teaching the Periodic Table, where the focus is on understanding the relationships between elements rather than simply memorizing their properties. The Periodic Table, as both content and tool, is important because it is an integral part of chemistry education, and many complex chemistry concepts are built on its foundation. Linking the Periodic Table with robotics technology can provide learners with a tangible representation of the Table's structure and an interactive learning experience that can help them develop a deeper understanding of abstract and difficult chemistry concepts.

The proposed study aims to minimize the aforementioned gap by introducing a novel approach to incorporate robotics in teaching specific chemistry concepts using the periodic table. Robotics technology has unique capabilities that traditional chemistry teaching methods and tools may not offer. For example, robotics technology can provide learners with visual and interactive learning experiences that simulate chemistry processes in the real world (Soh, Lim & Tan, 2019). This can help learners develop a deeper understanding of abstract and complex chemistry concepts, such as the Periodic Table. The use of robotics technology in teaching chemistry can involve programming robots to create a 3D model of the Periodic table or using robots to physically place elements on a 3D printed periodic table. This approach can provide learners with a tangible representation of the Periodic Table's structure, enabling them to interact with it in a hands-on manner.

Therefore, the approach involves implementing various strategies such as using robotics in assimilation, experimental-based teaching, and game-based teaching and learning, focusing on the periodic as both a tool and a system used to teach chemistry. The study will also contribute to the literature by investigating the unique contributions of robotics to teaching chemistry using the Periodic Table. This study will provide a new way of exploring the Periodic Table that is engaging, interactive, and effective. The integration of robotics into Chemistry teaching and learning using the Periodic Table presents a significant opportunity for enhancing learners' learning experiences. As such, in this study, robotics will be used to simulate chemical reactions, conduct experiments, and introduce game-based learning, which can make the learning process more engaging, interactive, and effective. Hence the research question: What affordances does integrating robotics in a concept-based approach to teaching chemistry with the emphasis on the periodic table as content and tool bring to promote deeper and more meaningful learning?

OBJECTIVES OF THE STUDY

The study aims to assess the effectiveness of integrating robotics technology and concept-based teaching approaches in enhancing learners' understanding of abstract chemistry concepts, specifically focusing on the periodic table. The objectives include evaluating the impact of robotics integration, addressing challenges in periodic table learning, exploring concept-based teaching methods, and promoting deep, meaningful learning experiences, ultimately contributing to the advancement of innovative strategies in STEM education.

MATERIALS AND METHODS

Research Design

This research study aimed to investigate the affordances robotics technology brings when integrated with a concept-based teaching approach in chemistry education. In addition, this integration must specifically focus on the understanding of the periodic table, to achieve deeper and more meaningful learning. The study utilized a mixed-method approach with multiple data-gathering methods to provide a comprehensive analysis of the outcomes. Both concept-based teaching and robotics technology are reported to encourage learners to think critically, analyse problems, and find innovative solutions (Weng & Lu, 2018). An experimental design was utilized, which involves a pre-test and post-test comparison group method. Participants were assigned to two groups. That is, the experimental and the control groups from different schools and teachers. Both groups were subjected to the same pre-test before teaching. The experimental group received instruction that included the use of robotic technology with a concept-based approach, while the control group was subjected to teacher-focused teaching (TFT) and a concept-based approach.

Sample Selection and Respondents

This study took place in the Gauteng area of South Africa and the sample selection process used a multistage random sampling approach. A multistage random sampling strategy involves segmenting the population into distinct stages, or clusters. To produce a representative sample, the researchers then randomly choose samples from each stage or cluster (Acharya et al., 2013). The selection process for both learners and teachers involved several steps to ensure a comprehensive and balanced representation. For the learners, the process began with the random selection of one district from the Gauteng region, followed by the random selection of two schools within that district. This random selection helps eliminate potential biases and ensures a fair representation of schools in the study.

Once the schools were chosen, learners were purposely selected from each school based on specific criteria. These criteria included being a grade 10 high school learner, currently enrolled in a chemistry class, and having no prior exposure to robotics in education. By setting these criteria, the study ensures that the learners selected are relevant to the research question and are more likely to yield reliable results. A sample of 40 learners from each school was selected, with 20 learners assigned to the comparison group and 20 learners assigned to the experimental group. This division allows confirmatory analyses of whether the integration of robotics with concept-based approach has indeed brought the difference considering that the two groups used different approaches. With the control group, the researcher wanted to see what the different changes are, relative to the control group.

To establish a baseline, all learners had to take a pre-test before the intervention began. This pre-test assesses their initial knowledge and serves as a benchmark for measuring the impact of integrating robotics with concept-based approach in chemistry. On the other hand, the selection of teachers was based on specific criteria related to their qualifications and experience. Teachers had to currently teach a chemistry class at one of the selected schools, have at least two years of experience teaching grade 10 chemistry, and be willing to participate in a 3-week training program on using robotics in teaching chemistry. These criteria ensure that the selected teachers possess the necessary knowledge and skills to effectively integrate robotics with concept-based approach in a chemistry class.

Two teachers from each school were selected, with one teacher randomly assigned to the comparison group and the other teacher assigned to the experimental group. This random assignment helps maintain group equivalence and reduces potential biases. In total, the study involved four chemistry teachers who met the selection criteria and were willing to participate. Overall the selection process for both learners and teachers in this study aims to ensure a representative and balanced sample, while also considering the specific criteria relevant to the research question and the integration being implemented.

Data gathering procedure and analyses.

The research was conducted in the selected schools, with learners and teachers assigned to either the comparison or experimental group. Teachers in the experimental group received three weeks of training on using robotics for simulations, experimentation, and game-based learning, with the aim of promoting deeper and more meaningful learning. To assess the impact of robotics integration on the learners' understanding of the periodic table, qualitative data were collected through the analysis of text, specifically focusing on knowledge representation. Learners' responses were analyzed qualitatively to determine the representation of their understanding and to assess the depth of their learning.

Quantitative data was also collected to evaluate the achievement of learners in the experimental and comparison groups. Pre- and post-intervention tests were administered to measure performance and engagement. Descriptive statistics, such as mean and standard deviation, were utilized to analyze the data quantitatively, providing a measure of the learners' achievement on the specified learning objectives (see Figure 1).

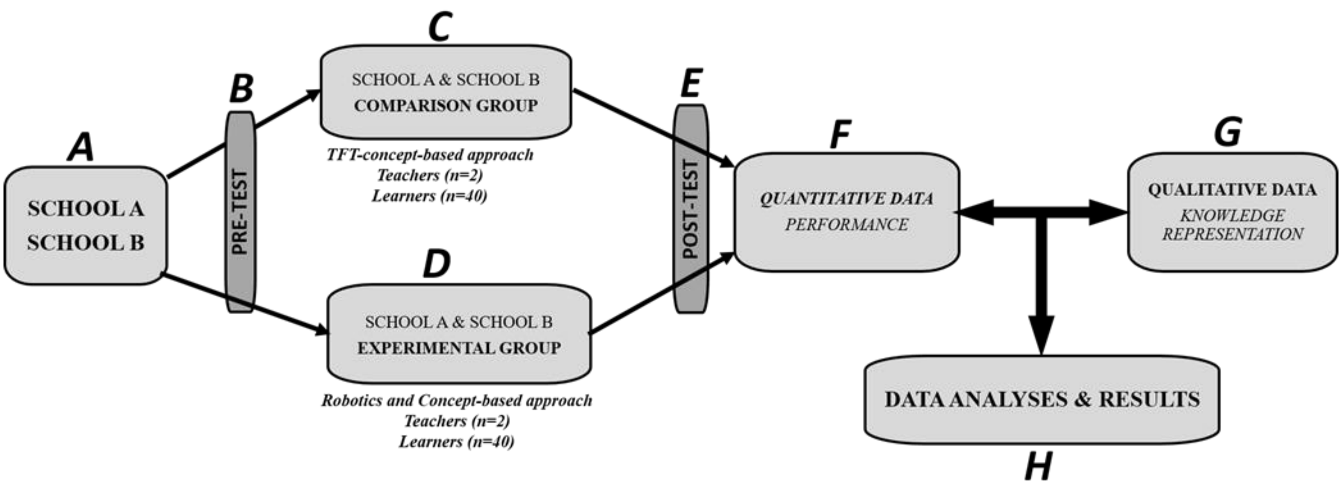

Figure 1: The Experimentation Process

Results and Discussion

The purpose of the study presented in this paper was to illustrate the deliberate use of the periodic table while investigating the possibilities of concept-based learning and robotics in the teaching of chemical concepts. The investigation into how using robotics technology in conjunction with the periodic table as a teaching tool in chemistry education may affect learners' knowledge construction and/or reconstruction was directed by the research question. Investigating how robotics technology affects learners' comprehension and utilization of periodic table content and system (i.e., as a tool) was the primary objective of the study. The research specifically attempts to investigate how learners' reconstruction of their knowledge in the field of chemistry is assisted by the usage of robots, concept-based approach, and periodic table.

Factors affecting the nature of science, aspects of incorporating technology that allow it to enhance chemistry education, aspects of highlighting concepts that accomplish the same, the contribution of PT as a tool and content, and the indication of deeper and more meaningful learning are all taken into consideration when analyzing the data. The researchers initially ascertained the effect of incorporating robotics with a concept-based methodology on the teaching and learning of chemistry concepts. For Teacher 1, Teacher 2, Teacher 3, and Teacher 4, the results are thus shown in Tables 1-3 (Appendix A).

Furthermore, the study analyzed the impact of Concept-Based Approaches (CBA) integrated with robotics on learners' understanding of chemistry concepts. The standard deviation values indicate that the post-test scores for each group are somewhat variable, but the CBA with the integration of robotics had an apparent significant impact on learners' performance, as shown by the higher standard deviation value for the experimental group (T2). The results of the T1 and T3 comparison groups' results indicate that the conventional teaching methods alone might not be sufficient in developing learners' understanding of chemistry concepts. However, learners in T1 had a higher pre-test score, indicating prior effective learning of chemistry concepts.

Therefore, there is an apparent indication that robotic technologies and CBA by themselves might not consistently enhance learners' comprehension of chemistry concepts, as seen in the T2 experimental group results. On the other hand, the T4 experimental group results demonstrate a significant improvement in learners' understanding of chemistry concepts. This may be associated with the combined use of robotics and CBA. In school A, the comparison group (T1), there is a small improvement in post-test scores, indicating some level of learning. However, the experimental group (T2) shows a larger improvement in post-test scores, suggesting that integrating robotics with concept-based learning may have facilitated deeper understanding and meaningful learning. In school B, Both the comparison group (T3) and experimental group (T4) show minimal improvement in post-test scores, indicating limited learning in the traditional teaching approach as well as in the integration of robotics with concept-based learning.

About Ausubel's theory of meaningful learning (1968)., the findings suggest that integrating robotics with concept-based learning in School A (T2) led to better knowledge representation and improved performance, as demonstrated by the significant increase in post-test scores. It is, likely that this integration facilitated the meaningful learning process by helping learners connect new concepts with their prior knowledge and build on existing mental frameworks. However, in School B (T4), the integration did not result in significant improvement, indicating that other factors might have influenced the learning outcomes. Thus, the results may imply that meaningful learning can be facilitated, and learner knowledge representation can be positively influenced by combining robotics with concept-based learning. It is crucial to consider additional contextual elements that could affect how effective this integration is, such as individual characteristics, learner engagement, and teaching strategies.

To address why the integration of robotics in the combined approach did not result in a significant difference, the researcher probed the learners' knowledge representations of chemistry concepts with the periodic table as the focus tool (Table 4). Learners who generally performed higher and who displayed the most significant changes in their knowledge representations between pre-test and post-test per teacher were selected. As a result, the researcher reported on these four learners to highlight the effectiveness/difficulties of integrating robotics with concept-based teaching methods in promoting learning.

The study recognizes the importance of learners' knowledge reconstruction and incorporates aspects of both Marton and Säljö's (1976) six Hierarchies of Learning and Ausubel's theory of meaningful learning. An analytical framework that combines elements from both frameworks is used to assess learners' understanding of the periodic table. Ausubel's theory highlights the significance of meaningful learning and the organization of new information about existing cognitive structures. It emphasizes the role of prior knowledge in constructing new understanding. Marton and Säljö's framework categorizes learning into surface, deep, and strategic approaches and considers factors that influence the nature of learning. Despite having distinct perspectives, both theories emphasize the importance of deep understanding and organization.

In the context of teaching chemistry using the periodic table, the researchers implement an approach that involves designing open-ended and authentic scientific questions related to the properties and patterns of elements in the periodic table. Learners work collaboratively in small groups to investigate these questions using robotics as a tool for observation, measurement, and data recording. Teachers provide feedback and support to help learners refine their research questions and synthesize their findings into written reports. This approach aims to promote deep and meaningful learning by engaging learners in hands-on activities, connecting new information with prior knowledge, and encouraging critical thinking and collaboration.

The table (Table 4) presents the knowledge representation of four individual learners (L1 – L4) in a chemistry class for both their pre-test and post-test. The findings depict various levels of knowledge representation in each learner. Learner 1 (L1) has a higher level of knowledge representation in the post-test, scoring 32% in the pre-test compared to 72% in the post-test. In the pre-test, L1's responses focused mainly on memorizing isolated facts without fully comprehending the underlying principles. For instance, the learner defines boiling point as "the change in which liquid changes into gas," indicating a misconception and/or surface learning. Whereas, in the post-test, L1's responses indicate some understanding of the concepts, such as the general trend in ionization energy and the difference between chemical change and physical change. The learner’s knowledge representation is mainly focused on surface learning, where the learner focuses more on memorizing isolated facts and/or information rather than understanding them fundamentally. This could signify that the learner's experience with standardized testing reinforces surface learning. The teacher’s conventional teaching style also could be a contributing factor to this.

Learner 2 (L2) has a higher level of knowledge representation, as reflected in their higher post-test score of 74% compared to their low pre-test score of 32%. In the pre-test, L2's responses indicate a focus on memorizing isolated facts without fully understanding the underlying principles. For example, they define boiling point as "the point where water changes from liquid to gas that is the boiling point," without providing a comprehensive explanation. However, in the post-test, L2 presents a thorough understanding of various chemical concepts, such as the forces of attraction between molecules and the trend in ionization energy. The learner’s knowledge representation is primarily focused on qualitative and quantitative deep learning by providing a comprehensive explanation of the concepts.

Learner 3 (L3) has a lower level of knowledge representation, portraying surface and ineffective deep learning tendencies. L3's score increased from 16% in the pre-test to 44% in the post-test. During the pre-test, L3's responses mainly revolved around memorizing isolated facts without fully comprehending the underlying principles. For instance, they define boiling point as "the heating curve that the temperature increases from a lighter and the water starts to boil," indicating surface learning. In contrast, during the post-test, L3's responses provide a comprehensive explanation of the concepts, such as the relationship between inter-molecular forces and the boiling point. However, the responses still demonstrated some ineffective deep learning habits, struggling to connect new information with existing knowledge and lacking a comprehensive understanding of the subject matter. The learner’s knowledge representation is focused on surface and ineffective learning since the learner concentrates more on memorizing facts rather than trying to relate new information with existing knowledge. Hence, L3 may need different learning opportunities such as practical exercises or demonstrations that promote deeper learning.

Learner 4 (L4) has a high level of knowledge representation, primarily demonstrating tendencies of qualitative and quantitative deep learning. In the pre-test, L4 focused on memorizing isolated facts without fully comprehending the underlying principles, defining boiling point as "the change in which liquid changes into gas," indicating surface learning. On the contrary, in the post-test, L4's responses tend to focus on basic definitions, calculations, broader concepts, and relationships. The learner's understanding of the qualitative and quantitative aspects of the subject matter seems elevated. The response to calculating the relative atomic mass correctly in the pre-test demonstrates an understanding of quantitative deep learning to an extent, but this understanding seems concentrated on calculations rather than deeper comprehension of the subject. The teacher's integration of robotics with a concept-based teaching approach could have provided an adequate platform for L4 to develop sound knowledge in chemistry.

There are varying forms and accuracy levels of knowledge representation among the four learners. The findings for each learner suggest ways that chemistry teachers can approach learners learning from multiple perspectives to achieve a deeper understanding of the subject matter. For instance, adopting active engagement methods such as the integration of robotics with concept-based teaching and/or learning could help promote diverse learning approaches. This is evident from findings in Learners 2 and 4 who received instructions from such an approach and displayed promising deeper meaningful learning in chemistry.

CONCLUSION AND RECOMMENDATION

The purpose of the study was to explore the possibility of leveraging robotics technology and a concept-based teaching strategy to teach chemistry topics linked to the emphasis on the periodic table as a teaching tool, as specified in the study's introduction and through the research question. A quasi-experimental approach was employed in the study, and both quantitative and qualitative methods were used to collect data. The findings showed that using robotics technology in conjunction with a concept-based approach helps learners grasp things more deeply and conceptually. The results are consistent with theories of constructivism and cognitive load (Piaget, 1970; Vygotsky, 1978; Sweller, 1994; Paas & Sweller, 2012), which contend that experiential learning and formalized frameworks facilitate the creation of new knowledge. The findings corroborate other studies (Chittum & Jones, 2017; Miller & Gerace, 2011), which show that multidisciplinary teaching and hands-on activities enhance learners' understanding of STEM (science, technology, engineering, and math) disciplines.

By emphasizing the benefits of using robotics technology in the teaching of periodic table-based chemical concepts, the study adds to the body of literature. An interactive learning experience has been made possible by the use of robots, which has given learners the ability to visualize, manipulate, and experiment with complicated scientific phenomena. As a result, there are a lot of opportunities for STEM education to improve learner understanding owing to this integration. Future studies might look into how well robotics technology integrates with other branches of chemistry, such as organic or physical chemistry. To improve learning results, studies may also look into the possible effects of combining robotics with other cutting-edge teaching strategies. Furthermore, research in the future might explore the obstacles to robotics technology adoption in poor nations and devise plans to overcome them. The potential for improving learners' conceptual comprehension and problem-solving abilities is evident when robotics technology is combined with a concept-based approach. Therefore, additional research is needed to look at the benefits of this strategy for raising learner interest and comprehension in science classes, especially when teaching periodic table-based chemical ideas.

REFERENCES

Acharya, A. S., Prakash, A., Saxena, P., & Nigam, A. (2013). Sampling: Why and how of it. Indian Journal of Medical Specialties, 4(2), 330-333.

Alimisis, D. (2012, September). Robotics in education & education in robotics: Shifting focus from technology to pedagogy. In Proceedings of the 3rd International Conference on Robotics in Education (Vol. 9).

Ausbel, D. P. (1968). Educational Psychology: A Cognitive View. New York: Holt, Rinehart, and Winston.

Cao, C., Vernon, R. E., Schwarz, W. H., & Li, J. (2021). Understanding periodic and non-periodic chemistry in periodic tables. Frontiers in Chemistry, 8, 549296.

Chittum, J.R., & Jones, A.T. (2017). The impact of interdisciplinary teaching on science students' learning: A literature review. Journal of STEM Education Research, 1(2), 14-26.

David, G. A. (2018). Introduction to mechatronics and measurement systems. MCGRAW-HILL EDUCATION.

Ding, L., Zhu, X., Chen, G., & Mechtley, A. (2018). Use of 3D printing technology in chemistry education: A systematic review. Chemistry Education Research and Practice, 19(2), 617-629.

Herald, C. (2019). Sphero robots and the periodic table. Science Scope, 43(4), 53-57.

Kalotschke, M., & Blasczyk, M. (2017). The role of educational robotics based on LEGO in chemistry education for fostering interest and motivation among high school students. Journal of Chemical Education, 94(7), 858-864.

Kara, A, & Bayırtepe, E. (2021). The effectiveness of robotics in chemistry education: A systematic review and meta-analysis. Computers & Education, 170, 104279. https://doi.org/10.1016/j.compedu.2021.104279

Lim, C. P., Bahri, S., & Goh, W. W. (2020). Learning Physics through Robotics: A Pedagogical Approach. Robotics, 9(1), 18. https://doi.org/10.3390/robotics9010018

Lim, K. Y., Bahri, N. A., & Goh, W. Y. (2020). Integrating Robotics Technology into Chemistry Education: A Multi-Case Study. Journal of Chemical Education, 97(6), 1571-1578. DOI: 10.1021/acs.jchemed.0c00018

Lin, T. J., & Lai, C. L. (2018). Cultivating computational thinking abilities and STEM career interests through the application of educational robotics activities. International Journal of STEM Education, 5(1), 51.

Liu, J., Golonka, E., & Curin, A. (2019). Enhancing chemistry learning through robotics. Journal of Chemical Education, 96(2), 247-253.

Marton, F., & Säljö, R. (1976). On qualitative differences in learning: I—Outcome and process. British journal of educational psychology, 46(1), 4-11.

Mhlongo, T., & Sedumedi, T. D. (2023). Problems with Periodic Table Theory-Praxis in Chemistry Topics Teaching. Indonesian Journal of Science and Mathematics Education, 6(2), 192-205.

Miller, E.R., & Gerace, W.J. (2011). Instructional methods and student responses predict peer acceptance of a collaborative hands-on science task. Contemporary Educational Psychology, 36(3), 240-252.

Morales-Menendez, R., Garcia-Méndez, A., & Zizumbo-Villarreal, L. (2016). Design of a robotic system for teaching the periodic table to visually impaired students. Journal of Intelligent & Robotic Systems, 82(1), 139-155.

Morales-Menendez, R., Garcia-Méndez, P., & Zizumbo-Villarreal, D. (2016). Traditional knowledge and seed selection criteria in landraces of chía (Salvia hispanica L.) in México. Genetic Resources and Crop Evolution, 63(3), 491-506.

Mudau, A. V., & Nkopodi, N. (2015). Teachers' anecdotes on the teaching of periodic tables in the senior phase. Journal of educational studies, 14(1), 125-140.

Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. Educational Psychology Review, 24(1), 27-45.

Piaget, J. (1970). Science of education and the psychology of the child. New York, NY: Orion Press.

Sánchez, H., Martínez, L. S., & González, J. D. (2019, November). Educational robotics as a teaching tool in higher education institutions: A bibliographical analysis. In Journal of Physics: Conference Series (Vol. 1391, No. 1, p. 012128). IOP Publishing.

Scerri, E. (2019). The periodic table: its story and its significance. Oxford University Press.

Soh, J. Y., Lim, K. Y., & Tan, S. C. (2019). A Design-Based Research on Integrating Robotics into Chemistry Education in Singapore Secondary Schools. In A. Lazinica & C. Calafate (Eds.), Intelligent Systems Design and Applications (pp. 21-32). Springer. DOI: 10.1007/978-3-030-20214-4_3.

Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. Learning and Instruction, 4(4), 295-312.

Traver, V. J., Leiva, L. A., Martí-Centelles, V., & Rubio-Magnieto, J. (2021). Educational videogame to learn the periodic table: Design rationale and lessons learned. Journal of Chemical Education, 98(7), 2298-2306.

Turchi, C., Aleotti, J., & Caselli, S. (2020). Educational robotics and tangible programming tools: A review. Robotics, 9(2), 41.

Valko, N. V., & Osadchyi, V. V. (2021, June). Teaching robotics to future teachers as part of education activities. In Journal of physics: Conference series (Vol. 1946, No. 1, p. 012016). IOP Publishing.

Verner, I. M., & Revzin, L. B. (2017). Robotics in school chemistry laboratories. In Robotics in Education: Research and Practices for Robotics in STEM Education (pp. 127-136). Springer International Publishing.

Vygotsky, L.S. (1978). Mind in Society: The Development of Higher Psychological Processes. Cambridge, MA: Harvard University Press.

Weng, J., & Lu, L. (2018). Promoting scientific literacy in robotics-based science and technology education. Journal of Computers in Education, 5(4), 421-437.

Wiggins, G. P., & McTighe, J. (2011). The understanding by design guide to creating high-quality units. ASCD.