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Contributions of Cognitive Ergonomics to the Teaching of Elementary Electricity in High School: A Study of the Concepts of Voltage, Current, and Resistance

Georges EL AHL , Naim Rouadi (EL)

Ph. D, Education Research Laboratory (LRE), Saint Joseph University, Beirut; Physics Teacher, Lebanese Secondary Schools

Emeritus Professor of Mathematics Didactics, Education Research Laboratory (LRE), Saint Joseph University, Beirut

ABSTRACT: Elementary electricity remains a major source of conceptual difficulty for high school students, particularly regarding the understanding of voltage, electric current, and resistance. This study examines the contribution of cognitive ergonomics to improving the teaching and learning of these concepts through a comparative quasi-experimental design involving approximately 250 secondary students. A traditional lecture-based approach was compared with a guided ergonomic instructional design integrating principles of cognitive load theory and a structured use of the hydraulic analogy. Quantitative analyses of pre- and post-tests, complemented by qualitative analysis of learners' written productions, show significantly greater learning gains for students exposed to the ergonomic approach. Results indicate improved conceptual differentiation, reduced alternative conceptions, and more coherent reasoning. The findings highlight the importance of ergonomically designed instructional materials and guided analogies in reducing extraneous cognitive load and fostering durable conceptual understanding in physics education.

KEYWORDS: Elementary electricity; Cognitive ergonomics; Voltage; Electric current; Resistance; Hydraulic analogy.

I. INTRODUCTION

Elementary electricity occupies a central place in high school physics curricula due to its structuring role in the understanding of electrical phenomena and its numerous applications. The concepts of voltage, electric current, and resistance are essential for the study of electrical circuits and condition access to more advanced knowledge in electrodynamics. However, these notions remain difficult for secondary school learners to master, as demonstrated by numerous studies in physics education research (Viennot, 1996; Duit & von Rhöneck, 1998; Redish, 2003).

Learners frequently display alternative conceptions, such as confusion between voltage and current, the perception of current as a localizable or "consumable" entity, and the interpretation of resistance as a simple material obstacle (Shipstone et al., 1988; Closset, 1983; Psillos, Tiberghien, & Koumaras, 1988; McDermott & Shaffer, 2018). These difficulties are exacerbated by the abstract nature of electrical quantities and the need to coordinate multiple semiotic registers, including verbal language, diagrams, and mathematical formulas (Duval, 1995; Tiberghien, 2000; Ainsworth, 2023).

Traditional teaching practices, often centered on lecture-based instruction and the rapid introduction of formal laws, are insufficient to consolidate conceptual understanding. Instructional materials, particularly textbooks, may reinforce these difficulties when they juxtapose representations without adequate guidance (Ainsworth, 2006; Mayer, 2020; Schneider et al., 2022; El-Ahl, 2025).

Cognitive ergonomics, grounded in cognitive load theory, provides a framework for optimizing the design of instructional materials, reducing extraneous cognitive load, and fostering deep learning (Sweller, 2019; Sweller, Ayres, & Kalyuga, 2023). In the teaching of electricity, it allows for the evaluation of diagram readability, content organization, and the presentation of physical laws. The reasoned use of analogies, such as the hydraulic analogy, can facilitate access to electrical concepts provided that their correspondences and limitations are explicitly addressed (Duit, 1991; Gentner & Smith, 2012; Richland & Simms, 2015; El-Ahl, 2025).

This article analyzes the contributions of cognitive ergonomics to the teaching of elementary electricity in high school by comparing a traditional lecture-based approach with an ergonomic approach integrating the hydraulic analogy and the analysis of instructional materials.

II. THEORETICA FRAMEWORK

A. Elementary Electricity in Secondary Education

The concepts of voltage, current, and resistance form an interdependent system whose understanding relies on abstract relationships that are not directly observable. Learners tend to perceive current as a material object, voltage as a property of the generator, and resistance as a simple obstacle, which limits their appropriation of electrical laws, particularly Ohm's law (Closset, 1983; Shipstone et al., 1988; Psillos et al., 1988; McDermott & Shaffer, 2018).

These difficulties also stem from the simultaneous mobilization of multiple semiotic registers (diagrams, mathematical language, graphical representations), whose coordination is not spontaneous for learners (Duval, 1995; Ainsworth, 2006).

B. Cognitive Ergonomics and Learning in Physics

Cognitive ergonomics analyzes the interactions between learners, tasks, and instructional materials with the aim of optimizing cognitive processes. According to cognitive load theory, the limited capacity of working memory significantly influences learning effectiveness (Sweller, 1988; Sweller et al., 2019). Cognitive load is commonly divided into intrinsic load (content complexity), extraneous load (information presentation), and germane load (schema construction) (Sweller et al., 2011).

In electricity education, intrinsic load is high, whereas extraneous load can be reduced through ergonomically designed instructional materials applying principles such as information segmentation, visual coherence, signaling, and text–image integration (Mayer, 2020; Schneider et al., 2022).

C. Cognitive Ergonomics and the Didactics of Electricity

Cognitive ergonomics provides a framework for analyzing the design of textbooks, visual materials, and teaching practices. Overloaded diagrams, lack of hierarchical organization, and the juxtaposition of semiotic registers tend to reinforce conceptual misunderstandings (Ainsworth, 2006; Tiberghien, 2000).

Analogies, particularly the hydraulic analogy, facilitate access to electrical concepts by linking them to more familiar quantities. Their effectiveness depends on the explicit clarification of correspondences and limitations between the source domain and the target domain (Duit, 1991; Gentner & Smith, 2012; Richland & Simms, 2015). Recent research shows that integrating this analogy into an ergonomic instructional design reduces extraneous cognitive load and improves conceptual understanding (El-Ahl, 2025).

Thus, this theoretical framework articulates the didactics of electricity, cognitive ergonomics, and instructional design in order to improve physics learning at the high school level.

III. RESEARCH PROBLEM AND OBJECTIVES

A. Research Problem

Despite sustained efforts by teachers and the availability of instructional materials, the teaching of elementary electricity in high school continues to generate substantial learning difficulties. As highlighted in the theoretical framework, the conceptual complexity of voltage, electric current, and resistance, combined with the coexistence of multiple symbolic representations, leads to persistent confusions and alternative conceptions among learners (Shipstone et al., 1988; Tiberghien, 2000; McDermott & Shaffer, 2018).

Traditional instructional practices, largely based on lecture-centered transmission of electrical laws and formal equation manipulation, have limited effectiveness in fostering deep conceptual understanding. Moreover, instructional materials such as textbooks, diagrams, and analogies may increase extraneous cognitive load when they are poorly structured, insufficiently guided, or cognitively overloaded (Ainsworth, 2006; Mayer, 2020; Schneider et al., 2022).

The hydraulic analogy is a commonly used instructional tool intended to facilitate access to electrical concepts. However, its effectiveness strongly depends on the conditions of its implementation and on the explicit articulation of correspondences and limits between the source and target domains (Duit, 1991; Gentner & Smith, 2012; Richland & Simms, 2015). In this regard, a recent doctoral study showed that integrating the hydraulic analogy within an instructional design grounded in cognitive ergonomics—including guided visual supports, information segmentation, and explicit discussion of the analogy's limitations—enhances learners' conceptual understanding while reducing extraneous cognitive load (El-Ahl, 2025).

Accordingly, the central research problem addressed in this study can be formulated as follows: How can instructional designs for teaching elementary electricity be conceived and implemented in ways that reduce extraneous cognitive load, promote effective use of analogies, and foster learners' conceptual understanding of voltage, electric current, and ohmic resistance?

B. Research Objectives

Based on this research problem, the study pursues three main objectives, aligned with the three axes of the doctoral research.

The first objective is to identify and analyze learners' conceptual difficulties in elementary electricity (voltage, current, resistance) through the examination of textbooks and traditional teaching practices, in order to determine sources of cognitive overload and conceptual confusion.

The second objective is to assess the contribution of cognitive ergonomics to the design of instructional materials in electricity, drawing on principles such as content segmentation, hierarchical organization, diagram readability, and text–image integration, with the aim of promoting meaningful learning and deep processing of concepts.

The third objective is to evaluate the effectiveness of the hydraulic analogy, when embedded within a guided ergonomic instructional design, in supporting learners' conceptual differentiation between voltage, current, and resistance, by comparing learning outcomes under two instructional modalities: a traditional lecture-based approach and a guided ergonomic approach.

C. Research Questions

In line with these objectives, the study addresses the following research questions.

What are the main conceptual difficulties encountered by learners in elementary electricity, and to what extent are these difficulties related to existing instructional materials and teaching practices?

How does the application of cognitive ergonomics principles improve the presentation of electrical concepts and reduce extraneous cognitive load?

To what extent does the integration of the hydraulic analogy within a guided ergonomic instructional design enhance learners' conceptual understanding of voltage, current, and resistance?

IV. METHODOLOGY

A. Research Design

This study adopts a comparative quasi-experimental design, combining quantitative methods with qualitative analysis of learners' written productions. Its purpose is to evaluate the impact of an instructional design grounded in cognitive ergonomics and incorporating the hydraulic analogy on high school students' conceptual understanding of elementary electricity.

The methodological framework is derived from the doctoral research conducted by El-Ahl (2025), which compares two instructional modalities: a traditional lecture-based approach and a guided ergonomic approach.

B. Context and Participants

The study was conducted in Lebanese secondary schools implementing the official 1997 national curriculum. Participants were high school students who had not yet received systematic instruction on direct-current electrical circuits.

The sample consisted of approximately 250 learners, divided into two comparable groups in terms of academic level and prior knowledge.

The control group received traditional lecture-based instruction, while the experimental group was taught using an instructional design based on cognitive ergonomics principles.

C. Compared Instructional Designs

This methodological choice was motivated by the intention to rigorously assess differences in learning gains between two groups exposed to distinct instructional conditions, while controlling key variables such as content, instructional duration, and learners' academic level. The experimental protocol included the administration of a pre-test, the implementation of the instructional interventions according to group assignment, and the administration of a post-test identical to the pre-test.

C.1. Traditional Lecture-Based Approach

The traditional instructional approach relied on a frontal presentation of the concepts of voltage, electric current, and resistance, supported by oral explanations, textbook use, and the solving of standard exercises. Conceptual introduction was primarily based on electrical laws, notably Ohm's law, and mathematical relationships, with limited use of guided visual representations.

C.2. Guided Ergonomic Approach

The guided ergonomic instructional design was developed in accordance with principles derived from cognitive load theory. It incorporated progressive segmentation of instructional content, explicit hierarchical organization of concepts, coordinated text–image presentation aimed at reducing extraneous cognitive load, and guided use of the hydraulic analogy with explicit clarification of both correspondences and limitations.

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This approach relied on multimedia instructional materials, including a pedagogical video[1] capsule, and emphasized conceptual understanding prior to mathematical formalization.

D. Data Collection Instruments

Multiple instruments were used to collect complementary and reliable data. A pre-test was administered prior to instruction to assess learners' initial conceptions of voltage, current, and resistance. A post-test was administered after instruction, addressing the same concepts and intended to measure learning progression. In addition, a qualitative analysis of learners' written responses enabled the identification of recurrent errors and persistent alternative conceptions.

All instruments were aligned with the instructional objectives and validated by physics teachers and researchers in physics education.

E. Data Analysis Procedures

Quantitative data from pre-tests and post-tests were analyzed using descriptive and comparative statistical methods to compare mean performance levels and assess learning gains between the two groups.

In parallel, a qualitative analysis of learners' responses focused on identifying the types of reasoning employed, persistent conceptual misunderstandings, and the impact of the guided ergonomic approach on learners' understanding of the relationships between voltage, current, and resistance.

This combined analytical strategy allows for the integration of measurable outcomes with in-depth didactic interpretation.

F. Methodological Limitations

Although the study is based on a substantial sample, certain limitations must be acknowledged, particularly the quasi-experimental nature of the design and its dependence on specific school contexts. These limitations are discussed in order to clarify the scope and transferability of the findings.

V. RESULTS

A. Pre-test Results: Learners' Initial Conceptions

The analysis of the pre-test results highlights significant and recurrent conceptual difficulties among learners in both groups (control and experimental), confirming findings widely reported in the literature. The concepts of electric voltage, electric current, and resistance are frequently confused, particularly in the context of direct-current circuits.

A significant proportion of learners equate voltage with a form of current or consider it an intrinsic property of the generator, independent of the circuit. Others view electric current as being consumed by circuit components or as varying according to position in the circuit. Resistance is often interpreted as a localized obstacle rather than as a quantity characterizing an ohmic component. These results confirm the persistence of alternative conceptions previously identified by Shipstone et al. (1988) and McDermott and Shaffer (2018).

The mean scores obtained by the two groups on the pre-test show no statistically significant difference, indicating their initial comparability and validating the relevance of subsequent comparisons.

[1] https://www.youtube.com/watch?v=236xiOCtqek&feature=youtu.be

B. Post-test Results: Learning Progression

The post-test results show an overall improvement in performance in both groups, reflecting the effect of the instruction provided. However, this improvement is clearly more pronounced among learners who benefited from the guided ergonomic instructional design.

The experimental group achieved mean scores significantly higher than those of the control group, particularly on items assessing conceptual understanding of the relationships between voltage, current, and resistance. Learners in this group more frequently mobilized coherent reasoning based on physical quantities rather than relying solely on mechanical application of formulas.

In contrast, the control group still exhibited predominantly algorithmic responses, with a sometimes-fragmented understanding of concepts, despite a certain level of procedural mastery.

C. Comparative Analysis of Learning Gains

The analysis of learning gains, calculated from the difference between pre-test and post-test scores, reveals a significantly higher gain for the experimental group. This difference suggests that the instructional design based on cognitive ergonomics promotes more effective and more durable learning of elementary electricity concepts.

The results notably show:

- A clearer distinction between voltage and current;
- A more stable understanding of the role of resistance in the circuit;
- A reduction in errors related to the localization of current or the consumption of current.

These observations confirm the positive impact of reducing extraneous cognitive load on conceptual learning.

D. Qualitative Analysis of Learners' Productions

The qualitative analysis of written responses reveals notable differences in the types of reasoning mobilized by learners in the two groups. Learners in the experimental group use more conceptual justifications, relying on functional diagrams and coherent verbal explanations.

The hydraulic analogy, when integrated in a guided and explicitly explained manner, appears to be an effective lever for supporting understanding, provided that its limitations are clearly stated. Learners in the experimental group seem better able to identify relevant correspondences between the two domains and to avoid certain inappropriate generalizations.

In contrast, in the control group, the analogy is sometimes mobilized implicitly or incorrectly, reinforcing certain alternative conceptions.

E. Synthesis of Results

Overall, the results show that:

- Initial conceptual difficulties in elementary electricity are significant and persistent.
- The guided ergonomic approach leads to a significant improvement in learners' conceptual understanding.
- The controlled integration of the hydraulic analogy, combined with an ergonomic design of instructional materials, contributes to reducing extraneous cognitive load and fostering deeper learning.

These results empirically confirm the research hypotheses and open the way for an in-depth discussion of the contributions of cognitive ergonomics to physics education.

VI. DISCUSSION

A. Interpretation of the Results considering the Theoretical Framework

The results obtained confirm theoretical contributions concerning learning difficulties in elementary electricity at the secondary school level. The confusions observed among learners in the pre-test, particularly between electric voltage, electric current, and resistance, are consistent with findings reported in numerous previous studies in physics education research (Shipstone et al., 1988; Tiberghien, 2000; McDermott & Shaffer, 2018). These difficulties can be partly explained by the abstract nature of these quantities and by the simultaneous mobilization of multiple representational registers (symbolic, graphical, and mathematical).

The significant improvement in performance observed among learners who benefited from the guided ergonomic instructional design fully aligns with cognitive load theory. By reducing extraneous cognitive load through better structuring of instructional materials and progressive segmentation of content, the instructional design promotes more efficient information processing in working memory, thereby facilitating the construction of stable conceptual schemas (Sweller, 1988; Sweller et al., 2019; Schneider et al., 2022).

B. Contributions of Cognitive Ergonomics to the Teaching of Elementary Electricity

The comparison between the two instructional approaches highlights the value of cognitive ergonomics in teaching fundamental electricity concepts. Unlike the traditional lecture-based approach, which often emphasizes formal manipulation of equations, the guided ergonomic approach places conceptual understanding at the core of the instructional design.

The results show that streamlined visual supports, explicit coordination between text and diagrams, and clear hierarchical organization of information help limit sources of cognitive overload. These findings are consistent with the multimedia design principles proposed by Mayer (2020) and underscore the importance of thoughtful instructional material design in physics education.

C. Role and Limitations of the Hydraulic Analogy

The hydraulic analogy emerges as a relevant instructional tool for supporting understanding of the relationships between voltage, current, and resistance, provided that it is integrated within a rigorous pedagogical framework. The results indicate that when correspondences between the source domain (hydraulics) and the target domain (electricity) are explicitly addressed, the analogy promotes more coherent reasoning and reduces certain alternative conceptions.

However, the observations also confirm the limitations of this tool when it is used implicitly or without proper guidance. In such cases, the analogy may reinforce erroneous interpretations, particularly the idea that electric current is consumed or stored. These findings align with the work of Duit (1991) and Gentner and Smith (2012), who emphasize the need for systematic clarification of the limits of analogies.

D. Perspective in Relation to Previous Research

The results of this study extend and enrich previous research in electricity education by providing empirical validation of the value of an approach that integrates both cognitive ergonomics and the reasoned use of analogies. In particular, they confirm the conclusions of McDermott and Shaffer (2018) regarding the insufficiency of purely procedural approaches in fostering durable conceptual understanding.

Furthermore, this study makes an original contribution by showing that the effectiveness of the hydraulic analogy is enhanced when it is embedded within an instructional design explicitly aimed at reducing extraneous cognitive load, as demonstrated in the doctoral research of El-Ahl (2025).

VII. DIDACTIC AND PEDAGOGICAL IMPLICATIONS

A. Implications for the Design of Teaching Sequences

The results of this study highlight the need to rethink the design of teaching sequences in elementary electricity at the secondary school level. It appears essential to prioritize a progressive conceptual development that allows learners to construct stable meanings before the formal introduction of mathematical relationships. Such a progression helps limit confusions between voltage, current, and resistance, which are often observed when these quantities are introduced simultaneously and in an abstract manner.

The explicit integration of cognitive ergonomics principles into the planning of teaching sequences promotes clearer structuring of content and a reduction in extraneous cognitive load. This notably involves segmenting concepts, clearly hierarchizing information, and paying particular attention to coherence among the different representational registers used.

B. Implications for the Design of Instructional Materials

The results highlight the central role of instructional materials in either facilitating or hindering conceptual learning. Ergonomic instructional materials, characterized by simplified diagrams, explicit coordination between text and images, and the limitation of non-essential information, appear more effective in supporting learners' cognitive processing.

These findings call for a critical review of existing textbooks and digital resources in order to identify and correct potential sources of cognitive overload. The reasoned use of multimedia resources, particularly instructional videos designed according to multimedia learning principles, may serve as an effective lever for improving understanding of electrical concepts.

C. Implications for the Use of Analogies in Electricity

The study confirms that the hydraulic analogy can play a positive role in learning elementary electricity, if it is integrated into a rigorously structured instructional framework. The analogy must be explicitly introduced, accompanied by systematic work on the correspondences between the source and target domains, as well as on the limits of the analogy.

From a didactic perspective, this implies that analogies should not be considered as mere illustrations, but as genuine tools for conceptual mediation requiring explicit pedagogical guidance. Such an approach helps reduce the risk of reinforcing alternative conceptions and promotes more coherent reasoning among learners.

D. Implications for Teacher Education

The results of this research emphasize the importance of both pre-service and in-service teacher education in the principles of cognitive ergonomics and cognitive load theory. A better understanding of these principles would enable teachers to design learning situations that are more closely aligned with learners' cognitive capacities.

Teacher education should also include reflective work on the use of analogies, the design of instructional materials, and the analysis of students' errors and alternative conceptions. This approach would contribute to strengthening instructional effectiveness and improving the quality of learning in elementary electricity.

E. Perspectives for Research and Pedagogical Innovation

Finally, this study opens several avenues for future research. It would be relevant to extend this approach to other areas of physics in order to assess the transferability of cognitive ergonomics principles. Longitudinal studies could also be conducted to examine the durability of the observed learning gains.

Moreover, the development of ergonomic digital instructional resources integrating interactive simulations and guided multimedia materials represents a promising pathway for pedagogical innovation in physics education.

VIII. LIMITATIONS OF THE STUDY AND RESEARCH PERSPECTIVES

A. Methodological Limitations

Although this study provides significant results regarding the effectiveness of a guided ergonomic instructional design in teaching elementary electricity, several limitations must be considered.

First, the quasi-experimental nature of the study implies that the assignment of learners to groups was not fully random. Although the two groups were comparable in pre-test scores, contextual differences or unmeasured variables (motivation, classroom conditions, prior knowledge) may influence the results.

Second, the limited duration of the intervention represents a constraint. The study was conducted over only a few sessions, allowing assessment of the immediate impact of the ergonomic design, but providing no information on the long-term retention of concepts such as voltage, current, and resistance.

Third, the results are based on written tests and occasional qualitative analyses, which may not capture all cognitive processes mobilized by learners. Certain reasoning strategies or implicit conceptions may remain invisible, as systematic classroom observations or in-depth learner interviews were not conducted.

Finally, the study was carried out within the specific context of the 1997 Lebanese curriculum and a limited set of secondary schools. Generalization of the results to other cultural, curricular, or educational contexts should therefore be approached with caution.

B. Limitations Related to the Use of Analogies and Cognitive Ergonomics

The hydraulic analogy, although shown to be effective in this design, has intrinsic limitations. If poorly guided or used without explicit clarification of correspondences, it may reinforce alternative conceptions. The validity of the analogy therefore strongly depends on the quality of pedagogical guidance and the teacher's ability to explain the limits of analogical transfer.

Similarly, cognitive ergonomics principles were applied to a limited set of materials (diagrams, texts, and video capsules), restricting the scope of the study to these specific types of resources. The effectiveness of these principles on other materials or teaching modalities (virtual laboratories, interactive simulations) remains to be evaluated.

C. Research Perspectives

This study opens several promising avenues for future research:

- **Longitudinal research:** Examining the durability of learning gains over several months or years would help determine whether conceptual improvements achieved through the ergonomic approach remain stable over time and transfer to new contexts or problems.

- **Extension to other physics concepts:** Cognitive ergonomics principles and guided analogies could be applied to other challenging areas of physics (optics, mechanics, thermodynamics) to test the transferability of results and generalize pedagogical recommendations.
- **Diversification of instructional materials:** Integrating interactive simulations, virtual environments, or ergonomic digital applications could enhance instructional effectiveness and provide opportunities for adaptive learning.
- **Qualitative deepening:** Combining classroom observations, learner interviews, and analyses of reasoning strategies would allow a better understanding of the cognitive processes involved in learning electricity and using analogies.
- **Teacher education:** Investigating how training in cognitive ergonomics and controlled use of analogies can improve instructional effectiveness in different educational contexts.

D. Synthesis

In conclusion, although this study demonstrates that the integration of cognitive ergonomics and a guided analogy significantly improves understanding of elementary electricity, its methodological and contextual limitations must be acknowledged. Nevertheless, these limitations provide a fertile framework for future research aimed at generalizing the results, enhancing instructional designs, and exploring new teaching modalities tailored to learners' cognitive needs.

IX. GENERAL CONCLUSION

This study explored the teaching of elementary electricity at the secondary school level, focusing on electric voltage, current intensity, and resistance, through an approach integrating cognitive ergonomics principles and the reasoned use of the hydraulic analogy.

The results show that learners still face significant conceptual difficulties, primarily due to the complexity of the concepts, the multiplicity of symbolic representations, and teaching practices centered on lecture-based instruction and formal manipulation of formulas. These findings confirm the analyses of Shipstone et al. (1988), Tiberghien (2000), and McDermott & Shaffer (2018).

The integration of a guided instructional design based on cognitive ergonomics reduced extraneous cognitive load, improved the structuring of information, and strengthened learners' conceptual understanding. Furthermore, the hydraulic analogy, when explicitly guided and limited, facilitated the distinction between voltage, current, and resistance while avoiding the introduction of alternative conceptions. These results confirm and extend the work of Sweller (1988, 2011, 2019), Mayer (2020), and El-Ahl (2025).

The contributions of this research are multiple. Didactically, it provides concrete recommendations for designing teaching sequences and instructional materials in elementary electricity. Methodologically, it illustrates the value of combining quantitative measures (pre- and post-tests) with qualitative analyses to understand learners' cognitive processes. Pedagogically, it emphasizes the importance of training teachers in cognitive load management, the use of analogies, and the design of ergonomic instructional resources.

Finally, this study opens promising research perspectives, including the generalization of the approach to other physics concepts, longitudinal assessment of learning gains, use of interactive digital resources, and development of adaptive learning environments.

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