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Effect of a STEM approach on students' cognitive structures about electrical circuits

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Abstract

Background Electricity is a central concept in science curricula at all levels of education. Nevertheless, its invisible nature makes the concepts associated with it very difficult for students. Moreover, students have many alternative conceptions about concepts related to electrical circuits. This study aims to know the effect of a STEM (Science–Technology–Engineering–Mathematics) approach on students' cognitive structures about the topic of electrical circuits, as revealed through a Word Association Test (WAT). A study following a time series quasi-experimental research design was made to collect information about changes in students' cognitive structures before and after a learning sequence about electrical circuits. A nonequivalent control group approach was used, and two matching groups of students were used: a control group ($N=317$) and an experimental group ($N=321$). Students were attending the 9th grade (14–15 years old). Data analysis was made by construction of frequency tables, maps of the cognitive structures, and examination of the sentences written by students.

Results The results are indicative that, before the STEM approach, students' conceptions regarding electrical circuits are mainly related to students' daily experiences. However, after a STEM approach, the map of students' cognitive structures from the experimental group is more complex. Furthermore, the quality of the response words is different for each group. In the control group, most of the associations that students made were situated at a phenomenological level. However, in the experimental group, students made many associations related to the curricular contents.

Conclusions The STEM approach had a more noticeable effect on the development of students' cognitive structures on the topic of electrical circuits: based on the results, it can be concluded that this approach allowed students from the experimental group to achieve the learning goals, while students from the control group still retained many ideas that do not meet learning goals. Additionally, WAT has proven to be a suitable diagnostic method, as well as an instrument that can be used to evaluate the accomplishment of students' learning objectives.

Keywords STEM education, Word Association Test (WAT), Cognitive structures, Electric circuits, Electricity, Students' conceptions

Introduction

Electricity, and the concepts associated with it, is a central area in the curricula of Science and Physics at all levels of schooling, starting from elementary school. However, the invisible nature of electricity makes the concepts associated with it problematic for students because they are very abstract and complex, and this implies that their understanding depends on models, analogies, and metaphors (Carlton, 1999; Mulhall et al., 2001; Saputro et al., 2018). Moreover, although electricity is a daily concept, it is a very fertile area for alternative conceptions across all levels of education, countries, cultures, etc. (Afra et al., 2009; Turgut et al., 2011). Regarding alternative conceptions, we will use this term in a broad sense. This means that it accommodates preconceptions and misconceptions, i.e., students' conceptions

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that conflict with scientifically accepted ideas (Gilbert & Watts, 1983). According to Carlton (1999) and Chapman (2014), what makes the concepts related to electricity not easily understood by the students, is the fact that these phenomena occur inside the wires and, as such, it is not possible to directly observe what happens when the flow of electrons moves through the circuit.

Over the past four decades, there have been numerous studies describing students' conceptions about electricity, and related concepts, and the concept of electric current has been the most investigated one. Studies conducted by Osborne (1983) and Shipstone (1985) allowed the identification of four conceptual models related to electric current in a simple circuit composed of a battery, wires, and lamp. According to Model A (non-recursive/source–sink) the current moves from the battery to the lamp, via one wire, and there is no current from the lamp to the battery, via another wire. In the Model B (clashing currents) there is a movement of the current from the battery to the lamp, via each wire, and it collides in the lamp. The Model C (consumption/attenuation) is characterized by the current movement from the battery to the lamp and back to the battery, but there is more current moving from the battery to the lamp. It is assumed that current is consumed in the lamp. Finally, the Model D (same current/scientific) is equal to Model C, but the current remains the same. In a study conducted by Çepni and Keleş (2006) with 250 students (11–22 years old), the researchers found that Model A is predominant in younger students (5th grade), but that about half of the 9th graders use Model C. Also, Tsai et al. (2007), in a national study with 10,000 students (8th, 9th and 11th grades), concluded that a considerable percentage of them (38% attending 8th and 9th grades, and 27% from 11th grade) conceptualize the electric current in an electrical circuit according to Model C. Similarly, Suma et al. (2018) detected Model B in some of the 75 students who participated in the study, besides other 21 additional students' misconceptions. Based on the results obtained, these investigators concluded that only 22.4% of the students, who attended the 11th grade, had previous scientifically accepted concepts about electricity and related concepts.

In the literature, several studies describe the students' indistinct use of terms such as electricity, electric current, electricity, power, voltage, charge, etc. (e.g., Çepni & Keleş, 2006; Shipstone, 1988; Tsai et al., 2007; Turgut et al., 2011). According to several authors, these alternative conceptions originate other alternative conceptions such as the consideration of a battery as a constant current source and this is indicative of the confusion between electric current and voltage. Another alternative conception is the consumption of electric current by electrical equipment, which reveals the inability to distinguish electrical current and electricity (Shipstone, 1988; Tsai et al., 2007). In fact, and from the perspective of some authors, voltage is often conceptualized only as a result of a mathematical relationship or as an electric current's property (Psillos et al., 1988; Tsai et al., 2007).

In addition to the above-mentioned aspects, other alternative conceptions and difficulties of students related to the topic of electricity are described. For example, regarding electrical circuits, Afra et al. (2009) assessed the effect of an inquiry-based learning strategy on 9th grade (14–15 years old) students' conceptions of electricity. According to the pretest results, the occurrence of many of the alternative conceptions described in the literature was verified. Some of the identified alternative conceptions included the conceptualization of electrical current and electrical circuits (component order, type, operating mode, and representation). Moreover, students also considered the battery as a constant voltage source and had difficulties in understanding the concept of resistance and its role in a circuit (Afra et al., 2009). However, the results of the posttest showed that the inquiry-based learning approach had positive effects in fostering conceptual understanding of basic concepts in electricity. In a more recent study, Preston (2019) describes the use of diagrams in the development of the conceptual understanding of twenty students (aged 8–11 years old) concerning electrical circuits. According to the results obtained, and "regardless of prior knowledge, mid-upper primary students could make at least some sense of electric circuits by interpreting the diagram" (Preston, 2019, p. 1453).

Based on what was described, it is possible to conclude that students have poor previous knowledge and many alternative conceptions about concepts related to electric current and electrical circuits. Since alternative conceptions are generally robust and persistent, it is essential not only to diagnose them, but also to use appropriate teaching strategies that allow their change in accordance with what is scientifically correct.

In this sense, this study aims to know the effect of a STEM approach on students' conceptions about the topic of electrical circuits, as revealed through a Word Association Test (WAT). The study was oriented by the following research questions (RQ): RQ1-What are the initial conceptions, present in the students' cognitive structures, regarding the topic of electrical circuits?; RQ2-What is the effect of a STEM approach on the development of students' cognitive structures, and consequently on their conceptions, on the topic of electrical circuits?

Theoretical framework

STEM education

In the last decades, STEM education had a growing role in international educational policies, since it is essential in today's societies not only to train young people to follow and understand the importance of scientific and technological developments that occur, but also to captivate them to pursue careers in STEM areas (Chiu & Duit, 2011; OECD, 2019). According to the OECD (2019), in more than half of the OECD countries, there are less than 24% of students that obtain their degrees in STEM areas, when compared to the percentage of students who complete their studies in other areas. Despite the growing need for human capital in STEM areas, students tend not to follow these areas because they find that Science curricula are very difficult and not very relevant. Also, the perception of low self-efficacy regarding scientific areas, the lack of knowledge about career opportunities, and the dearth of contact with STEM professionals can contribute to students' lack of interest in these areas (Heras et al., 2020; Osborne et al., 2003; Palmer et al., 2017; Sjøberg & Schreiner, 2010).

Although there are different perspectives on STEM Education and what is Integrated STEM Education (e.g., McComas & Burgin, 2020; Ortiz-Revilla et al., 2022; Quinn et al., 2020; Wells, 2013), in this work the term STEM Education is used as a form of "involve a sense of the integration of the four constituent disciplines in various ways and levels rather than treatment of them as disciplines isolated from one another" (Park et al., 2020, p. 901). Moreover, in the context of this work, the term STEM approach is used to designate a student-centered learning sequence that in its set of classes allows the integration of the four STEM areas.

Several studies illustrate the potential of STEM Education, namely in the promotion of students' curiosity about natural phenomena (Crippen & Antonenko, 2018; Moore et al., 2015) and in the improvement of attitudes toward scientific areas, which promote increased motivation and interest towards these areas (e.g., Chittum et al., 2017; Glynn & Koballa, 2006; Shahali et al., 2017; Toma & Greca, 2018), as well as in students' intention to pursue careers in STEM areas (Christensen & Knezek, 2017; Kitchen et al., 2018; Wang, 2013). In addition to these aspects, STEM education is described as promoting the development of various skills, like problem-solving, critical thinking, and creativity (Guthrie et al., 2000; Hurley, 2001). Additionally, Stehle and Peters-Burton (2019) report that STEM education provides learning environments that encourage the development of twenty-first century skills such as knowledge construction, real problem-solving, communication skills, collaboration, the use of information and communication technologies, and self-regulation. Regarding STEM education as a facilitator of student learning and as a potentiator of reasoning processes, a literature review carried out by the National Research Council (National Research Council, 2014) on the effect of STEM education on student outcomes, led to the conclusion that it encompasses significant benefits, and various studies support this conclusion (Cotabish et al., 2013; Crotty et al., 2017; Gazibeyoglu & Aydin, 2019; Glynn et al., 2009; Knezek et al., 2013; Tati et al., 2017).

Cognitive structures and Word Association Tests (WAT)

The exploration of an individual's cognitive structures is very important when trying to understand the students' learning process (Tsai & Huang, 2002). Cognitive structures are hypothetical constructs that refer to the organization of concepts in memory. Although there are other definitions of cognitive structures, we adopt the one that states that they are defined as the relationships that are established between concepts, terms, propositions, facts, theories, raw data, and/or processes, and that are stored in long-term memory, in a hierarchical way (Shavelson, 1974; Taber, 2008).

According to the constructivist perspective of the learning process, prior knowledge is fundamental in cognitive development because it is the starting point for the organization and interpretation of new information (Piaget, 1978; Vygotsky, 1978). For Ausubel (1963), cognitive structures are the main factor in the construction of knowledge because they contain students' experiences and previous knowledge that will determine the reconstruction and processing of new information (Tsai, 2001). Thus, a poor cognitive structure will result in poor information processing or inefficient retention of new knowledge, which will have repercussions on students' academic results.

In this sense, since the knowledge of students' cognitive structures is essential for the promotion of meaningful learning, their exploration by teachers helps them to know what students already have in their memory and whether it is compatible with what is scientifically accepted. This will guide teachers in the implementation of pedagogical strategies that promote meaningful learning (Atabek-Yigit, 2015; Tsai & Huang, 2002). As such, the analysis of cognitive structures can act as a map to identify and overcome possible learning difficulties. In addition to allowing the understanding of to what extent the structure in students' memory overlaps with the structure of the disciplinary concept, knowledge of students' cognitive structures also allows to predict to what extent it helps students to solve problems and/or to develop higher order skills (Cardellini & Bahar, 2000) such as those involved in learning new scientific concepts: comparison, analysis, understanding, model building, elaboration, etc. (Kostova & Radoynovska, 2008).

Several methods have been proposed to investigate cognitive structures (Tsai & Huang, 2002) and one of them is the Word Association Test (WAT). WATs were initially developed by Johnson (1967) and consist of asking an individual to quickly indicate the first word (response word) he/she thinks of when he/she is presented with a particular word (stimulus word): his/her answer reveals the idea most strongly associated with the stimulus word (Cardellini & Bahar, 2000). Thus, WATs are considered a snapshot of the cognitive structures of individuals, i.e., of their cognitive structures in their raw state (Bahar et al., 1999).

WAT implementation consists of the initial selection, by the researcher, of relevant words (stimulus words) related to the topic under study. Afterward, these stimulus words are presented to the participants, and they are asked to write words (response words) associated with each of the stimulus words, in a short period of time (Bahar et al., 1999; Hovardas & Korfiatis, 2006; Nakiboglu, 2008). In this way, a WAT provides information on the quantity and variety of responses related to key concepts and allows one to unravel the complexity of the associations between the concepts and, consequently, the understanding of the topic in question. The data obtained through the implementation of a WAT can be represented in the form of maps that illustrate the cognitive structure of students, i.e., how students store information related to a given topic. A map characterized by an interconnected network of concepts is indicative of the ability to solve problems, since it allows students to move from one concept to another. On the contrary, a map characterized by isolated islands makes it more difficult for students to solve more complex problems since they are unable to mobilize knowledge related to concepts that are positioned on different islands (Cardellini & Bahar, 2000).

According to Şendur and Toprak (2017), studies that involve a WAT implementation can be divided into two groups: those applied in a single moment, that allow knowing the cognitive structures of students (e.g., Özcan & Tavukçuoğlu, 2018; Timur, 2012; Yildirir & Demirkol, 2018), and those that are applied at two different moments (pretest/posttest) and that aim to evaluate the development of students' cognitive structures (e.g., Nakiboglu, 2008). However, WATs do not allow knowing the nature of the associations that students establish between the terms (Gunstone, 1980). For this reason, some researchers suggest that a WAT should be complemented with other methods, namely interviews, freewriting, and concept maps (Derman & Eilks, 2016; Nakiboglu, 2008).

In the literature, several studies describe the utilization of WATs as a way to disclose cognitive structures. Studies concerning Physics include the one performed by Timur (2012) with 56 future teachers that allowed the researcher to conclude, based on WAT results, that the participants possessed alternative conceptions regarding mass, weight, velocity, acceleration, and gravitational force. Also, in a study with 35 elementary prospective teachers, Sadoglu and Durukan (2018) implemented a WAT about basic Physics concepts (force, motion, speed, velocity, acceleration, and displacement). These researchers found some alternative conceptions, namely with the force concept, which was associated with movement and power, and with velocity and speed concepts, that were considered indistinguishable (Sadoglu & Durukan, 2018). Other studies, involving students, include the one performed by Özcan and Tavukçuoğlu (2018) in which the implementation of a WAT about light, revealed that the cognitive structure of 136 secondary students (11th and 12th grades) was muddled and resulted in incorrect, unscientific explanations. Also, Türksever (2021) explored the cognitive structures of 202 middle and high school students about the energy concept and found some alternative conceptions in some words, although the quality of students' responses increased as the grades of students increased as well. Regarding the topic of electricity, we only found one study that used a WAT to reveal students' cognitive structures. This study was performed with 100 students attending the 8th grade and it was clear that students revealed a lack of knowledge and alternative conceptions regarding the concepts of current, voltage, and resistance (Balbağ & Karademir, 2020).

Methodology

This study followed a time series quasi-experimental research design (Gribbons & Herman, 1997), which allowed to collect information about changes in students' cognitive structures before and after a learning sequence about electrical circuits. To do this, a nonequivalent control group approach was utilized, and two matching groups of students were used: a control group and an experimental group.

In both groups, a set of lessons (learning sequence) about electrical circuits was implemented, but with different approaches: in the control group, lessons were essentially teacher-centered and in the experimental group students were exposed to a sequence of lessons that followed a student-centered STEM approach about the topic under study. Both learning sequences are described in a section ahead.

For the experimental group, students' selection was made regarding their teachers: they were students whose teachers voluntarily participated in a 50-h professional development program about STEM education. This program consisted of three stages: (1) planning of STEM activities in collaboration with the university team; (2) implementation of STEM activities in the classroom with students; and (3) post-lesson reflection of the results obtained with the students. The teachers of the students of the control group did not participate in the professional development program: they were teachers from the same schools as the teachers that participated in the professional development program, that teach students of the same grade.

Context and participants

The participants of this study were students from the 9th grade, belonging to 12 schools from the region of Lisbon, and each school had an experimental group and a control group, in a total of 24 classes. Overall, the experimental group was composed of 321 students (154 girls and 167 boys, average age 14.35 years) and the control group consisted of 317 students (151 girls and 166 boys, average age 14.28 years).

This study was approved by the ethics board of our institution. Schools and students' parents were informed about the objectives and nature of the investigation and asked for an informed consent agreement. They were also informed about the right to leave the research at any time. The answers given by the students were de-identified to guarantee their anonymity and the confidentiality of the collected data.

Learning sequences

The learning sequence following a student-centered STEM approach was implemented in the classroom with the experimental group for about 2 months (seven lessons of 90 min each). It involved four sequential activities that, taken as a whole, allowed the integration of the four STEM areas. The learning sequence allowed students to formulate hypotheses, plan experiments, build graphs, interpret the results, draw conclusions, and build a prototype using the design process. In this manner, it was possible to integrate science (from the exploration of phenomena related to electrical circuits); mathematics (from the exploration of direct proportionality and algebraic equations); technologies (from the exploration of videos, electrical circuits, and Arduino) and engineering (from the exploration of prototypes that involved the use of design processes). A summary of the four activities that constituted the learning sequence is presented in Table 1.

In the control group, the learning sequence followed a traditional approach, in which the teacher has a more preeminent role, centering the lesson on him/herself through an essentially expositive attitude. Also, the teacher introduced the concepts prior to any experimental activity and the performed activities were very teacher-oriented, with a pre-established protocol that students just needed to follow. A summary of this learning sequence, which comprises six lessons of 90 min and three lessons of 45 min, is presented in Table 2.

Despite the implemented approach, the main learning goals of the learning sequences are in accordance with the Portuguese curriculum and preconize that students are able to:

(1) Plan and assemble simple electrical circuits, schematizing them.
(2) Give examples of good and bad electrical conductors.
(3) Measure electrical physical quantities (voltage, electric current, resistance) using measuring devices and using the appropriate units, checking how the voltage and electric current varies in associations in series and in parallel.
(4) Relate electrical currents at various electrical points and voltages in simple circuits and evaluate the association of receivers in series and in parallel.
(5) Enunciate Ohm's law and apply it.

Data collection and analysis

Data collection was performed through the implementation of a WAT, whose objective was to evaluate the development of students' cognitive structures concerning concepts related to electricity, as a result of the implementation of a STEM activity.

Both experimental and control groups were given the same WAT at two different moments: a pretest and a posttest. The pretest, which corresponds to moment 1 (M1) was performed 3 weeks before the implementation of the STEM activity, in the case of the experimental group, and 3 weeks before the teaching of the contents through a traditional approach, in the case of the control group. The posttest, which corresponds to moment 2 (M2), was performed three weeks after the implementation of the STEM activity, in the case of the experimental group, and three weeks after the teaching of the contents through a traditional approach, in the case of the control group.

To promote word association, four stimulus words (*ELECTRIC CURRENT*, *VOLTAGE*, *RESISTANCE,* and *BATTERY*) were given to the students, each one on a separate sheet of paper. Furthermore, to prevent the chaining effect (i.e., to prevent students from associating words with the last response word given), the stimulus word was repeated five times down in each paper sheet: this aimed to ensure that students answered according to

Table 1 Summary of the learning sequence implemented in the experimental group

Activity	Description	Curricular contents about electrical circuits	Learning objectives regarding electrical circuits
Activity 1 (90 + 90 min)	This activity began with a short text in which students were faced with a problem: they had to illuminate a room in a house. This activity allowed students to formulate hypotheses, plan a laboratory experiment (construction of electrical circuits with different configurations and measurement of the intensity of electric current and voltage), and perform it	Simple electrical circuits Symbolic representation of electrical circuits Electrical circuits with lamps in series and in parallel Measurement of the intensity of the electric current and voltage (using an ammeter and a voltmeter)	Plan and assemble simple electrical circuits, schematizing them Measure electrical physical quantities (voltage, electric current) using measuring devices and using the appropriate units, checking how the voltage and electric current varies in associations in series and in parallel
Activity 2 (90 min)	This activity began with a short text in which students were faced with a problem: they had to select a material to isolate an electric wire. A set of materials was available, and the students planned and performed an experience that allowed them to evaluate what was the most appropriate material	Electrical conductors and insulators	Give examples of good and bad electrical conductors
Activity 3 (90 + 90 min)	This activity was based on the nature of science, and more specifically on the life of George Simon Ohm. The students investigated about the life of George Simon Ohm and about arguments that illustrate his ideas and work regarding Ohm's Law. The students later planned an experiment to verify Ohm's Law and constructed graphs that allowed them to explore direct and inverse mathematical relationships between variables. The analysis of graphs also allows students to give sense and define electrical resistance. Students can explore how electrical resistance is measured	Ohm's Law Electrical resistance	Relate electrical currents at various electrical points and voltages in simple circuits and evaluate the association of receivers in series and in parallel Measure electrical physical quantities (resistance) using measuring devices and using the appropriate units Enunciate Ohm's law and apply it
Activity 4 (90 + 90 min)	In this activity the students applied the acquired knowledge in the previous activities to build an electrical artifact, combining the engineering and technology components. The task was contextualized on NASA's theme "Mars Mission 2020" (https://mars.nasa.gov/mars2020/mission/overview/). Students had to visualize some videos that show the various types of robots created by NASA. After viewing the videos, students were asked to identify some of the features of the robots. Then, the students received a kit with different components and developed their projects that go through several phases: plan and draw (sketch), assemble the circuits, confer the electrical diagrams, and program the sensors (ultrasonic, temperature, and humidity) and movement of the wheels, until they reach the final product (shape and esthetics)	Apply the acquired knowledge to build an electrical artifact	All the above

Table 2 Summary of the learning sequence implemented in the control group

Lesson	Description	Curricular contents about electrical circuits	Learning objectives regarding electrical circuits
1 (90 min)	The teacher begins the theme with a short introduction on the importance of electricity in daily life, defines what is electric current, and identifies good and bad conductors of electric current. The teacher presents the components of a simple electrical circuit, including its function and operation	Simple electrical circuits Components of an electrical circuit Electrical conductors and insulators	Plan and assemble simple electrical circuits Give examples of good and bad electrical conductors
2 (90 min)	The teacher defines what voltage is and its SI unit (V, volt). The teacher presents the intensity of electric current and its SI unit (A, ampere). The teacher presents the measurement devices, as well as the way they connect. Resolution of exercises about the contents taught	Intensity of the electric current and voltage: definition, units, and measurement equipment (ammeter and voltmeter)	Measure electrical physical quantities (voltage, electric current) using measuring devices and using the appropriate units
3 (45 min)	Students perform an experimental activity, based on a provided protocol, with the objective of building a simple electrical circuit and make some measurements. The teacher makes the necessary material available for students and requests the answer to some post-laboratory questions	Construction of a simple circuit Measurement of the intensity of the electric current and voltage (using an ammeter and a voltmeter)	Plan and assemble simple electrical circuits Give examples of good and bad electrical conductors Measure electrical physical quantities (voltage, electric current) using measuring devices and using the appropriate units
4 (90 min)	The teacher reviews the concepts taught in previous lessons and presents the symbolic representation of the electrical circuits and their components. Resolution of exercises on the concepts taught and on the experimental activity	Symbolic representation of electrical circuits	Schematize electrical circuits
5 (90 min)	The teacher uses a simulation to present the associations of electrical components in series and in parallel. Exploration of the simulation by the teacher. The professor mentions how to interleave an ammeter in a circuit to measure the current in a branch of that circuit	Electrical circuits with lamps in series and in parallel	Measure electrical physical quantities (voltage, electric current) using measuring devices and using the appropriate units, checking how the voltage and electric current varies in associations in series and in parallel
6 (45 min)	Realization of an experimental activity, which aims to build electrical circuits with components in series and in parallel and perform measurements of voltage and electrical current intensity. The activity is oriented through a provided protocol	Electrical circuits with lamps in series and in parallel	Measure electrical physical quantities (voltage, electric current) using measuring devices and using the appropriate units, checking how the voltage and electric current varies in associations in series and in parallel
7 (90 min)	The teacher indicates the factors on which the electrical current that passes through a component of a circuit depends and defines electrical resistance. The teacher presents the SI unit of electrical resistance (Ω, Ohm)	Electrical resistance	Measure electrical physical quantities (resistance) using measuring devices and using the appropriate units
8 (90 min)	The teacher explores a simulation to discuss how the intensity of electric current varies with resistance to a constant voltage and enunciates Ohm's Law. Resolution of exercises on Ohm's Law	Ohm's Law	Relate electrical currents at various electrical points and voltages in simple circuits and evaluate the association of receivers in series and in parallel Enunciate Ohm's law and apply it
9 (45 min)	Based on an established protocol, students perform an activity to verify Ohm's law	Ohm's Law	Relate electrical currents at various electrical points and voltages in simple circuits and evaluate the association of receivers in series and in parallel Enunciate Ohm's law and apply it

the stimulus word in question. The selection of the stimulus words was made by the authors and by the teachers of the classes, considering the central concepts of the topic in question. Students were asked to write as many items (response words) as they could, associated with each stimulus word. To facilitate the reading, along the subsequent text, stimulus and response words will be both presented in italic. Furthermore, stimulus words will be also written in capital letters. Also, to disclose the nature of the associations, students were asked to write a sentence that included the stimulus word and the respective response word. The total time given to students to perform these tasks was 10 min.

The analysis of WAT data was performed based on the frequency map method, which consisted of the examination of the responses associated with the stimulus words. Students' response words were counted if they were considered as being valid, i.e., if they were meaningful and acceptable in terms of the topic under consideration. The collected data were first used to ascertain inter-judge reliability: each one of the authors analyzed independently the data and their analysis were compared, using as criteria the counting of the total of different response words. Following Miles and Huberman's (1994) method, the consensus among the authors/judges was greater than 91%, both for the pretest and for the posttest.

Subsequently, the frequency tables were constructed for the control group and for the experimental group (Tables 3 and 4). From these, it was possible to build the maps of the students' cognitive structures, at M1 and M2, regarding the control group (Figs. 1 and 3) and the experimental group (Figs. 2 and 4).

The construction of the maps of the cognitive structures of the students began by establishing the upper and lower frequency intervals. Considering both moments (M1 and M2), and for both groups (control and experimental), the upper limit of the maps of cognitive structures corresponds to frequencies of responses between 200 and 240. This limit was defined considering the highest frequency recorded for a response word: 235 students from the experimental group associated the word *Light/Lighting* with the stimulus word *ELECTRIC CURRENT*.

Table 3 WAT frequency table of the control group

	Stimulus words							
	ELECTRIC CURRENT		***VOLTAGE***		***RESISTANCE***		***BATTERY***	
Response words	**M1**	**M2**	**M1**	**M2**	**M1**	**M2**	**M1**	**M2**
ELECTRIC CURRENT	–	–	44	58	48	18	31	–
VOLTAGE	32	27	–	–	21	–	37	–
RESISTANCE	–	23	19	30	–	–	14	–
BATTERY	46	66	31	46	–	–	–	–
Electrical circuit	–	113	–	116	–	–	–	29
Electrical shock	207	135	127	126	17	34	79	46
Electricity	91	133	76	112	29	49	59	–
Light/Lighting	189	217	98	160	37	18	88	–
Energy	135	160	96	–	39	–	112	114
Lamp	101	140	73	35	31	–	68	73
Home appliances	98	131	78	133	66	51	56	31
Wires/cables	99	62	34	–	39	–	–	–
Danger	102	38	108	–	21	–	42	–
Electrical plugs	208	166	66	21	–	–	–	–
Sparks	104	–	88	–	–	–	–	–
Switchboard	96	–	79	–	–	–	–	–
Negative	20	30	–	20	–	–	52	57
Positive	19	25	–	17	–	–	44	68
Block	–	–	–	–	101	–	–	–
Stop	–	–	–	–	132	66	–	–
Effort	–	–	–	–	69	47	–	–
Power supply	–	–	–	–	–	–	–	75

Response words with $f < 80$, regarding all stimulus words (pretest): fluid, charger, solar, LEDs, copper, death, force, substance, eolic, buildings, fire, etc.

Response words with $f < 40$, regarding all stimulus words (posttest): fluid, death, copper, switch, lamp brightness, volt, ampere, ohm's law, positive, ammeter, voltmeter, etc.

Table 4 WAT frequency table of the experimental group

Response words	Stimulus words: *ELECTRIC CURRENT* M1	*ELECTRIC CURRENT* M2	*VOLTAGE* M1	*VOLTAGE* M2	*RESISTANCE* M1	*RESISTANCE* M2	*BATTERY* M1	*BATTERY* M2
ELECTRIC CURRENT	–	–	38	105	–	78	23	87
VOLTAGE	16	94	–	–	–	70	22	–
RESISTANCE	–	75	8	56	–	–	14	–
BATTERY	38	133	22	117	–	112	–	–
Electrical circuit	–	167	–	128	–	66	–	129
Electrical shock	218	122	118	80	–	–	82	–
Electricity	88	185	56	107	18	78	23	–
Light/Lighting	183	235	101	71	-	104	68	–
Energy	123	100	87	-	46	–	105	91
Lamp	77	172	36	39	49	–	35	151
Home appliances	113	112	91	-	55	–	78	–
Wires/cables	104	133	13	65	58	–	–	–
Danger	101	–	114	–	24	–	36	–
Electrical plugs	206	83	44	–	–	–	–	–
Sparks	111	–	109	–	–	–	–	–
Switchboard	107	–	66	–	–	–	–	–
Negative	24	82	–	94	–	–	45	131
Positive	26	95	–	87	–	–	42	134
Block	–	–	–	–	176	–	–	–
Stop	–	–	–	–	127	–	–	–
Effort	–	–	–	–	111	–	–	–
Power supply	–	–	–	–	–	44	–	184
Electrons	–	122	–	109	–	–	–	–
Volt	–	–	–	122	–	–	–	–
Ampere	–	104	–	–	–	–	–	–
Ammeter	–	134	–	–	–	–	–	–
Voltmeter	–	–	–	133	–	–	–	–
Ohm	–	–	–	–	–	109	–	–

Response words with $f < 80$, regarding all stimulus words (pretest): fluid, charger, solar, LEDs, copper, death, force, substance, eolic, buildings, fire, etc.

Response words with $f < 80$, regarding all stimulus words (posttest): ohm's law, conductivity, mathematical equation, multimeter, AC, DC, etc.

The lower limits were defined by the lowest frequency at which all the stimulus words appeared. For instance, in the control group, at M1, the last stimulus word to appear was the word *BATTERY*, which students associated with *Energy*, at $f = 112$. As such, for this group at M1, the lower level was defined as $120 > f \geq 80$. The establishment of the lower levels was done similarly for the remaining groups/moments and indicated in the figures presented in the "Results" section. According to the literature (e.g., Derman & Eilks, 2016; Nakiboglu, 2008), there are no strict guidelines that determine how the intervals' range should be established. Thus, we defined a range of frequencies of 40, for each level. This allowed the creation of a reasonable number of levels to be analyzed and discussed. Moreover, this assured that there were differences from one level to the next, within the same group/moment (for instance, the appearance of a new stimulus word) and that the results could be compared among the various groups/moments.

After the establishment of the limits and frequency intervals of the maps, the stimulus words were placed inside rectangles. Arrows were used to join the stimulus words with the response words given by the students. The thickness of the arrows and rectangles was determined by the value of the frequency of the response word to the stimulus word and represents the strength of the associations. For example, in Level 1 ($240 > f \geq 200$), the stimulus words that appeared were placed inside the thickest rectangles and were connected to the response words by arrows with the same thickness. Also, for each

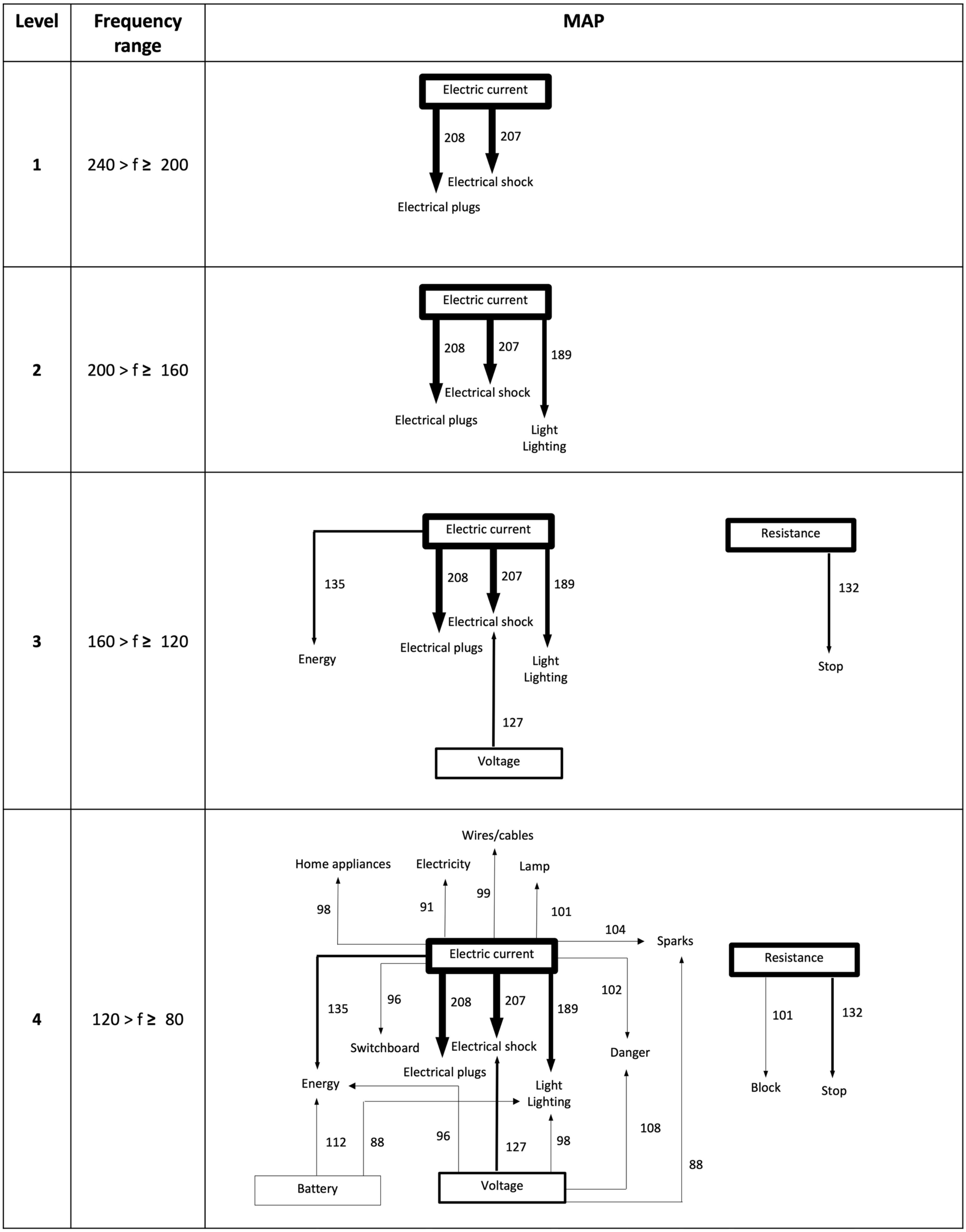


Fig. 1 Map of students' cognitive structures at M1 (control group)

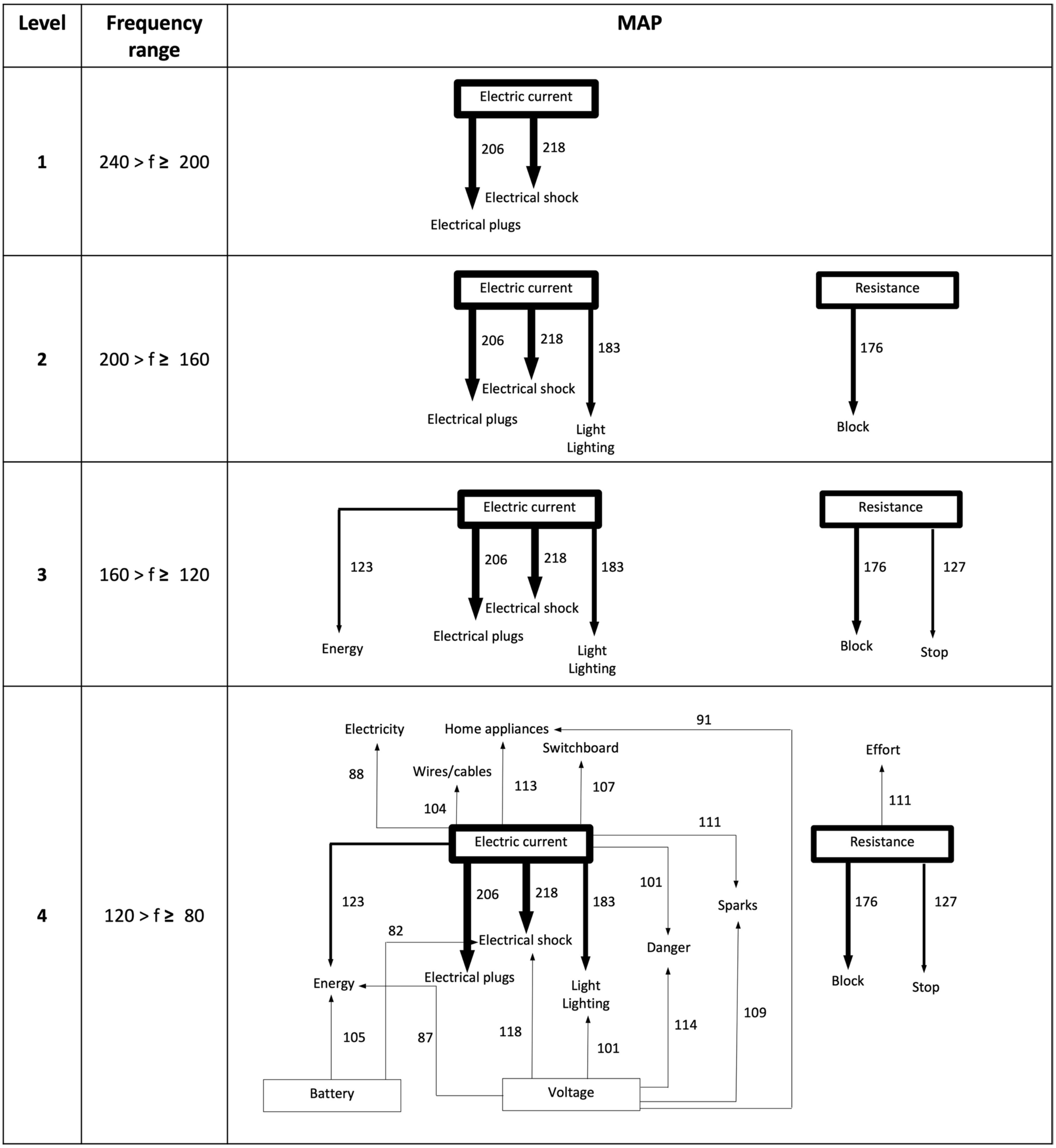


Fig. 2 Map of students' cognitive structures at M1 (experimental group)

association between the stimulus word and response word, the frequency value, is indicated near the arrow. These frequencies are the ones presented in Tables 3 and 4. In the following level (Level 2), the stimulus and response words that appeared in Level 1 were maintained and were added the stimulus and response words that emerge in the frequency range of Level 2 ($200 > f \geq 160$): the rectangles and arrows of these new words were thinner than the ones from Level 1. As such, it is possible to see in Level 2, some stimulus words with thicker rectangles (the ones with stronger associations, i.e., with higher frequencies) and stimulus words with narrower rectangles (the ones with weaker associations). Also, regarding the response words, some are associated with the stimulus words through heavier arrows, while others are associated through slimmer arrows. This procedure was made for all the levels until the last one, where the ultimate stimulus word appears in the thinnest rectangle and the response words appear with the narrower arrows. Thus, the thicker the arrow, the higher the frequency and, consequently, the stronger the association. As it will be described and discussed further on, Level 1 is less intricate but represents connections that most students made, while Level 5 has more connections but represents the conceptual understanding of fewer students. Consequently, by analysis of the cognitive maps, it was possible to get an idea of the strength and direction of the associations made by the students (Derman & Eilks, 2016; Nakiboglu, 2008).

Results

After analyzing and counting students' response words, frequency tables were constructed (Tables 3 and 4) and were used to draw the cognitive maps of both groups, which are presented in the following subsections.

As referred previously, some response words and/or associations made by students were not considered as being valid. For instance, some students associated the word *ELECTRIC CURRENT* with the word *Blood* in the following way: "*Blood* is blocked by the *ELECTRIC CURRENT* that runs the veins", and "If we put the fingers in the electrical plug, the *ELECTRIC CURRENT* sucks our *blood*". Other examples of associations that were not considered included: "My dad's car *BATTERY* broke down and we had to push it", "Humans' *RESISTANCE* causes conflicts between people", etc.

Additionally, sentences written by students were analyzed to reveal the nature of the associations. The presented sentences were selected as being representative of students' answers, i.e., we only present the sentences that illustrate the most common associations between words, although there are other sentences with slightly different formulations. For organizational reasons, the maps and students' sentences will be presented in two sections: one related to the pretest (M1) and another related to the posttest (M2).

Students' cognitive structures at M1 (Pretest)

The maps presented in Figs. 1 and 2 show that, for both groups, the stimulus word that appears at the strongest level of association (Level 1) is *ELECTRIC CURRENT*, associated with the response words *Electrical plugs* and *Electrical shock*. The sentences written by the students (Table 5) reveal the nature of the associations made and are related to the daily experiences of students. For instance, students state that "*Electric shocks* caused by *ELECTRIC CURRENT* are dangerous and deadly", and that "In the *electrical plugs* we have *ELECTRIC CURRENT* that serves to charge the mobile phones and my tablet".

At Level 2, and for both groups, students associate a new response word *Light/Lighting* to the stimulus word *ELECTRIC CURRENT* in the following way: "My room has *lighting* because the *ELECTRIC CURRENT* is in the lamp".

The stimulus word *RESISTANCE* appears at Level 2 for the experimental group and at Level 3 for the control group with words like *Block* and *Stop* associated with it. Also, at Level 3, and for both groups, a new response word (*Energy*) emerges. This word is associated with *ELECTRIC CURRENT,* and the most representative sentences of this association are: "The *ELECTRIC CURRENT* relates to the *energy* we have at home and at school" and "The *ELECTRIC CURRENT* decreases

Table 5 Some representative sentences written by students at M1

Association	Example of sentence (control and experimental group)
ELECTRIC CURRENT–Electrical shock	*Electric shocks* caused by *ELECTRIC CURRENT* are dangerous and deadly
ELECTRIC CURRENT–Electrical plugs	In the *electrical plugs* we have *ELECTRIC CURRENT* that serves to charge the mobile phones and my tablet
ELECTRIC CURRENT–Light/Lighting	My room has *lighting* because the *ELECTRIC CURRENT* is in the lamp
ELECTRIC CURRENT–Energy	The *ELECTRIC CURRENT* relates to the *energy* we have at home and at school The *ELECTRIC CURRENT* decreases as *energy* is consumed
VOLTAGE–Electrical shock	A high *VOLTAGE* can give an *electrical shock*
RESISTANCE–Stop	*RESISTANCE* is a barrier that *stops*
BATTERY–Energy	The *BATTERY* gives constant *energy* to toys *BATTERY energy* is consumed for the flashlight to give light
VOLTAGE–Danger	The *VOLTAGE* poses a *danger* of death
ELECTRIC CURRENT–Sparks	The short circuit *spark* caused by a large *ELECTRIC CURRENT* can lead to a fire

Since the sentences written by students belonging to the control and experimental group were similar, it was decided to consider them as being representative of both groups as *energy* is consumed". The stimulus word *VOLTAGE* appears at Levels 3 (control group) and 4 (experimental group), associated with the response word *Electrical shock,* and students claim that "A high *VOLTAGE* can give an *electrical shock*".

Ultimately, at Level 4, and for both groups, the last stimulus word (*BATTERY*) appears. According to the students, "The *BATTERY* gives constant *energy* to toys" and its "(…) *energy* is consumed for the flashlight to give *light*". Other associations made by the students are, for instance, the words *Wires/cables* and *Home appliances* with the word *ELECTRIC CURRENT* and the words *Danger* and *Sparks* to the word *VOLTAGE*, among others.

The total number of different words that appear in both maps is 18 (17 in the control group and 17 in the experimental group). Sixteen of these words are the same in both groups: only the words *Lamp* (in the experimental group) and *Effort* (in the control group) are not shared. This means that the maps presented in Figs. 1 and 2 have 89% of correspondence, regarding the type of words. Furthermore, only three common words (*Energy*, *VOLTAGE*, *RESISTANCE*) do not appear at the same level in both maps, and this results in 81% of similarity between both maps.

Despite not being the focus of this work, the analysis of the sentences written by the students, regarding the associations present in the maps of the cognitive structures, revealed that about 60% of the associations were alternative conceptions (61.3% for the control group and 62,9% for the experimental group).

Students' cognitive structures at M2 (posttest)

At M2, the maps of students' cognitive structures (Figs. 3 and 4) differ: while in the experimental group the map is characterized by the existence of four levels (Fig. 4), in the control group (Fig. 3) the last stimulus word only appears at frequencies below 80 (Level 5).

Regarding Level 1, in both groups, the stimulus word *ELECTRIC CURRENT* is associated with the word *Light/Lighting* and students wrote that is the electric current that "allows *light* in my room".

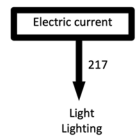
At Level 2, there are some differences between the cognitive structures of students that belong to the control group and the ones from the experimental group. In the control group a new stimulus word appears (*VOLTAGE*) connected to the word *Light/Lighting* because "The high *VOLTAGE* gives great illumination". In the experimental group, however, is the stimulus word *BATTERY* that emerges. For the students that belong to this group, "The *BATTERY* can be a *power supply*" and, as such, this word appears linked to the response word *Power supply*.

Additionally, and still regarding Level 2, new response words appear associated with the stimulus word *ELECTRIC CURRENT*. In the control group, the students mentioned the words *Electrical plugs* and *Energy*, and in the experimental group the words *Electricity*, *Electrical circuit,* and *Lamp* were indicated by the students. Examples of the sentences written by the students were: "The *ELECTRIC CURRENT* that reaches the *electrical plugs* allows me to charge my phone", "Wind *energy* can generate *ELECTRIC CURRENT*", "*Electricity* is the *ELECTRIC CURRENT* that is due to the movement of the *electrons* in the *circuit*", "The *electrical circuit* is the path of the *ELECTRIC CURRENT*", and "The *lamp* lights up when the *ELECTRIC CURRENT* passes through the *electrical circuit*".

In the next level (Level 3), for the control group, no new stimulus word appears. However, new response words are associated with the stimulus words previously present in the map: *Lamp* and *Electricity* linked to *ELECTRIC CURRENT* and *Home appliances* and *Electric shock* connected to both stimulus words. Regarding these associations, students claim, for instance, that "The *ELECTRIC CURRENT* circulates, and the *lamp* lights up" and that "*Electricity* is the *ELECTRIC CURRENT* of a closed *circuit*". Other examples include phrases like "You get a *shock* from the *ELECTRIC CURRENT*" and "My *dryer* is plugged in and has a high *VOLTAGE*". More sentences are presented in Table 6.

The Level 3 of the experimental group is characterized by the appearance of a new stimulus word (*VOLTAGE*) and students associate it with *Volt*, *Voltmeter,* and *Electrical circuit*. Students from the experimental group are aware that "The *VOLTAGE* unit is the *volt*", that "The *voltmeter* measures the circuit *VOLTAGE*", and that "The *BATTERY* in the *electrical circuit* creates a *VOLTAGE*". Additionally, in this level, students associate new response words to the stimulus words *ELECTRIC CURRENT* (e.g., *Electrons*, *Ammeter*) and *BATTERY* (e.g., *Negative*, *Positive*). Representative sentences of these and of the remaining associations are presented in Table 6.

The stimulus word *BATTERY* appears at Level 4 in the control group, linked to the word *Energy*. This association is explained by the students as "*BATTERY energy* is consumed for my tablet to work". Also, new response words are connected to the already present stimulus words: *Electrical circuit* and *Electrical shock* connected to both *ELECTRIC CURRENT* and *VOLTAGE*, and *Electricity* linked to *VOLTAGE*. In what concerns the experimental group, Level 4, is characterized by the appearance of the last stimulus word (*RESISTANCE*) that, according to students' sentences, "(…) can be a component of the *circuit* that is connected to a *BATTERY*", and "*Ohm* is the name of the one who invented the law and is the unit of *RESISTANCE*". Also, it is observable that new response words were associated with the stimulus words

<table>
<tr><th>Level</th><th>Frequency range</th><th>MAP</th></tr>
<tr><td>1</td><td>240 > f ≥ 200</td><td>
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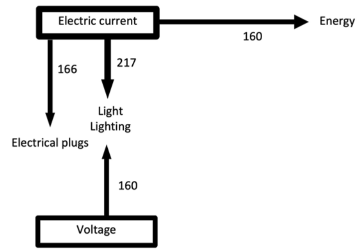
<tr><td>2</td><td>200 > f ≥ 160</td><td>
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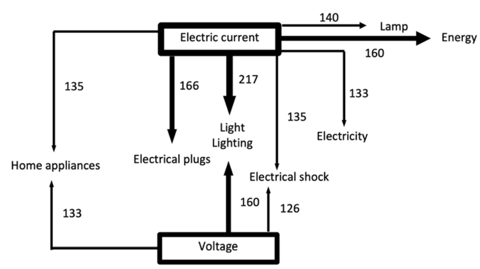
<tr><td>3</td><td>160 > f ≥ 120</td><td>
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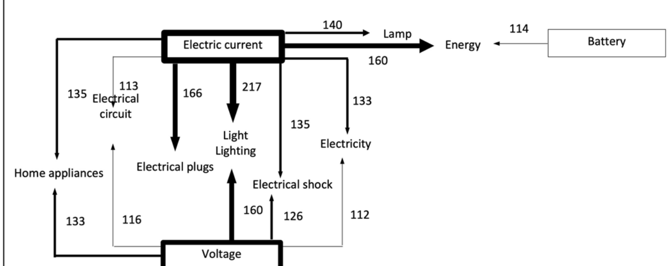
<tr><td>4</td><td>120 > f ≥ 80</td><td>
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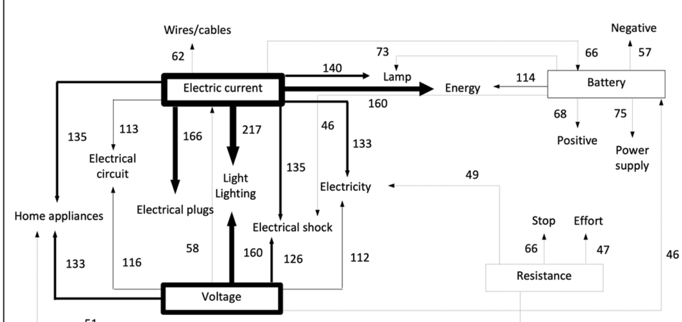
<tr><td>5</td><td>80 > f ≥ 40</td><td>
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Fig. 3 Map of students' cognitive structures at M2 (control group)

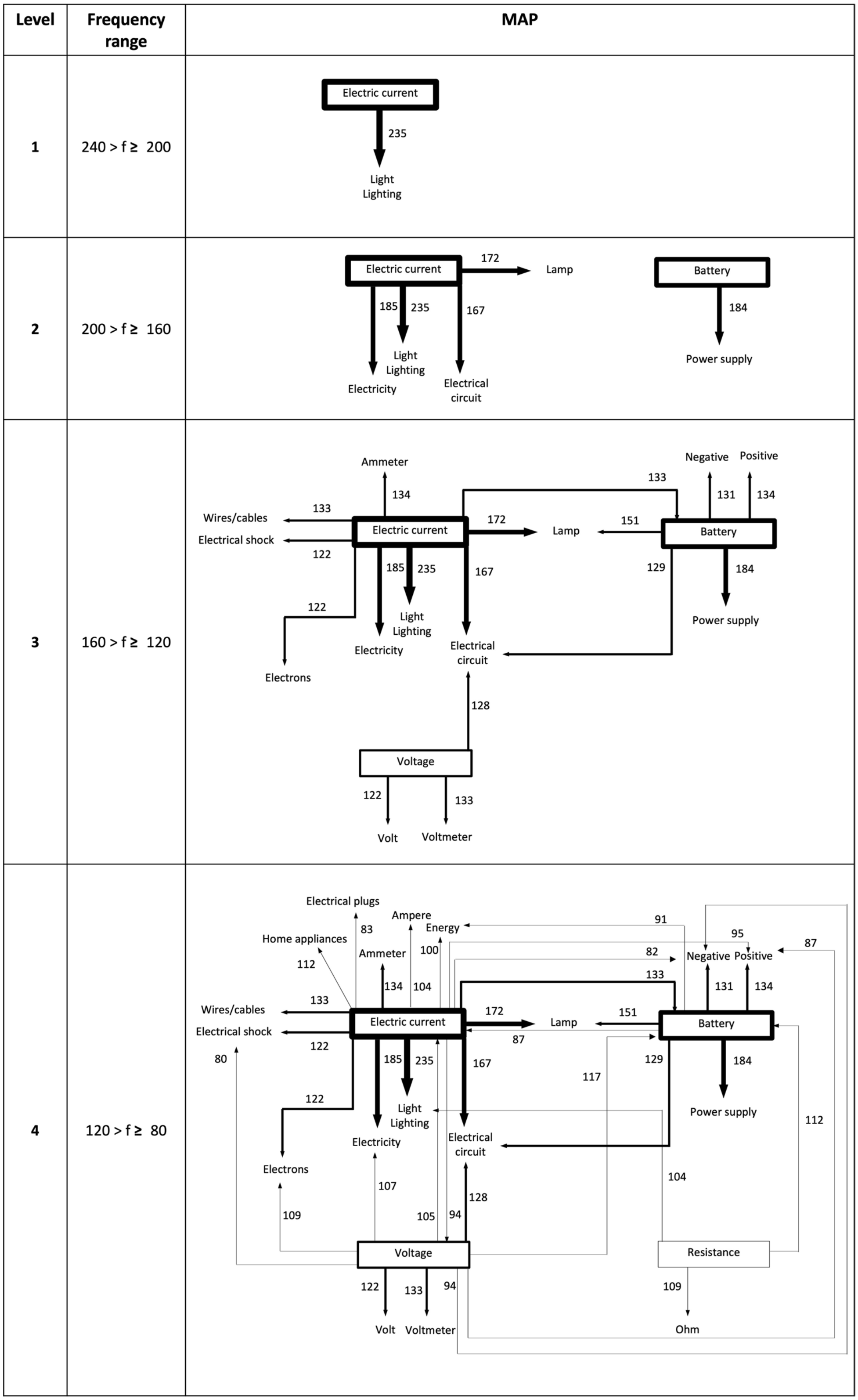

Fig. 4 Map of students' cognitive structures at M2 (experimental group)

Table 6 Some representative sentences written by students at M2

Association	Control group	Experimental group
ELECTRIC CURRENT–Light/Lighting	The *ELECTRIC CURRENT* allows *light* in my house	I have *light* in my room because the *ELECTRIC CURRENT* circulates in the electrical circuit
ELECTRIC CURRENT–Electrical plugs	The *ELECTRIC CURRENT* that reaches the *electrical plugs* allows me to charge my phone	N.A
ELECTRIC CURRENT–Energy	Wind *energy* can generate *ELECTRIC CURRENT*	*ELECTRIC CURRENT* can be produced from solar *energy*
VOLTAGE–Light/Lighting	The high *VOLTAGE* gives great *illumination*	N.A
ELECTRIC CURRENT–Lamp	The *ELECTRIC CURRENT* circulates, and the *lamp* lights up	The *lamp* lights up when the *ELECTRIC CURRENT* passes through the electrical circuit
ELECTRIC CURRENT–Electricity	*Electricity* is the *ELECTRIC CURRENT* of a closed circuit	*Electricity* is the *ELECTRIC CURRENT* that is due to the movement of the electrons in the circuit
ELECTRIC CURRENT–Electrical shock	You get a *shock* from the *ELECTRIC CURRENT*	High *ELECTRIC CURRENT* can give a *shock*
ELECTRIC CURRENT–Home appliances	The *ELECTRIC CURRENT* is for the iron and I can iron	The refrigerator needs *ELECTRIC CURRENT* to operate
VOLTAGE–Home appliances	My dryer is plugged in and has a high *VOLTAGE*	N.A
BATTERY–Energy	*BATTERY energy* is consumed for my tablet to work	N.A
ELECTRIC CURRENT–Electrical circuit	The *ELECTRIC CURRENT* circulates in the *ELECTRICAL CIRCUIT*	The *electrical circuit* is the path of the *ELECTRIC CURRENT*
VOLTAGE–Electrical circuit	The *electrical circuit* has a *VOLTAGE*	The battery in the *electrical circuit* creates a *VOLTAGE*
BATTERY–Positive	The *BATTERY* has a *positive* pole and a negative pole	The *BATTERY* poles are *positive* and negative
BATTERY–Power supply	The *BATTERY* is the *power supply* of the circuit	The *BATTERY* can be a *power supply*
ELECTRIC CURRENT–Wires/cables	The *ELECTRIC CURRENT* passes through electrical *wires* and lamps	Electrical *wires* allow the passage of *ELECTRIC CURRENT*
ELECTRIC CURRENT–BATTERY	The *BATTERY* is one of the elements of an electrical circuit through which the *ELECTRIC CURRENT* passes	The *ELECTRICAL CIRCUIT* has a *BATTERY* that provides electric current
RESISTANCE–Stop	*RESISTANCE* is for electricity to *stop*	N.A
ELECTRIC CURRENT–Ammeter	N.A	To measure the intensity of the *ELECTRIC CURRENT* in the electrical circuit I use the *ammeter*
ELECTRIC CURRENT–Electrons	N.A	The *ELECTRIC CURRENT* is due to the flow of *electrons*
BATTERY–Negative	N.A	The *BATTERY* has a *negative* pole
VOLTAGE–Volt	N.A	The *VOLTAGE* unit is the *volt*
VOLTAGE–Voltmeter	N.A	The *voltmeter* measures the circuit *VOLTAGE*
RESISTANCE–Ohm	N.A	*Ohm* is the name of the one who invented the law and is the unit of *RESISTANCE*
ELECTRIC CURRENT–Ampere	N.A	*ELECTRIC CURRENT* is measured in *amperes*
VOLTAGE–Electrons	N.A	The *electrons* remain in the circuit and are oriented because of the *VOLTAGE*
VOLTAGE–ELECTRIC CURRENT	N.A	The *VOLTAGE* is related to the generator of the electrical circuit, through which the *ELECTRIC CURRENT* passes
BATTERY–Lamp	N.A	To light the *lamp*, I have to have a *BATTERY*
RESISTANCE–BATTERY	N.A	*RESISTANCE* can be a component of the circuit that is connected to a *BATTERY*
RESISTANCE–Light/Lighting	N.A	The high electrical *RESISTANCE* means that there is less current flow, and the brightness of the lamp is lower
VOLTAGE–BATTERY	N.A	The *BATTERY* has negative and positive poles that relate to the *VOLTAGE*

In the sentences, only the words that were associated by the students are evidenced. For example, the sentence "The *VOLTAGE* is related to the generator of the electrical circuit, through which the *ELECTRIC CURRENT* passes" was written by students regarding the association *ELECTRIC CURRENT* and *VOLTAGE,* although there is also an association with *Electrical circuit*.

N.A. not applicable

ELECTRICAL CURRENT, *VOLTAGE,* and *BATTERY*. Further details of these associations, namely their nature, are presented in Table 6.

For the control group, the last stimulus word (*RESISTANCE*) appears at Level 5, and it is associated with the words *Stop*, *Effort*, *Electricity*, and *Home appliances*.

According to students' sentences, the most mentioned idea is that "*RESISTANCE* is for *electricity* to *stop*".

At M2, the total number of different words that appear in both maps is 24 (18 in the control group and 22 in the experimental group), and 16 of these words are the same in both groups. This means that the maps presented in Figs. 3 and 4 have 67% of correspondence, regarding the type of words. Regarding the levels at which the words appear, only 3 of the 16 common words appear at the same levels in both groups (*ELECTRIC CURRENT*, *Light/Lighting*, and *Electrical shock*). As such, at M2, there is only 19% of similarity between both maps.

As for M1, at the posttest, an analysis of the sentences written by the students, regarding the associations present in the cognitive structures' maps was performed. This analysis showed that, in the control group, 38.7% of the associations were alternative conceptions, while in the experimental group these comprise 18.5% of the associations.

Discussion

The results presented in the previous section are discussed in this section, taking into account the research questions that guided this study.

RQ1: What are the initial conceptions, present in students' cognitive structures, regarding the topic of electrical circuits?

To answer this research question, it was assumed that, at M1, the maps of students' cognitive structures for both groups were enough similar to consider that both groups shared the same "starting point". As described in the "Results" section, the words that appear on both maps (Figs. 1 and 2) are essentially the same. Also, the frequencies at which each word appears are almost the same, which means that they were mentioned by the same number of students, despite the group under consideration.

Thus, regarding RQ1, students who participated in this study had initial conceptions essentially related to their experiences. As such, at M1, students' ideas about electrical circuits are essentially related to the phenomenological level: students' cognitive structures do not include scientific concepts, nor ideas that provide an explanation, or the sense of understanding, of how electrical circuits work.

As can be seen in Figs. 1 and 2, students' response words and their statements (Table 5) report mainly to the use of household appliances like electrical plugs, lights, and diverse equipment. Additionally, the associations made by the students at M1 reveal that there is a perception about the risks of electricity: words like *Electrical shock* and *Danger* appear associated with *ELECTRIC CURRENT* and *VOLTAGE*. These results are in accordance with those described in the literature in which the students recognize that electric current allows electrical appliances to function, but do not understand how electric current is conducted within a circuit (Pliatou & Stavridou, 2004). In fact, and according to Solomonidou and Kakana (2000), younger children perceive electricity as static (being inside wires, sockets, lamps, etc.), similar to what was referred by the participants in our study. According to Pilatou and Stavridou (2004), this happens because wires and cables are usually hidden inside walls. Also, in literature is described the association that students establish between electric current and danger (Cokelez & Yurumezoglu, 2009).

The results concerning the stimulus word *RESISTANCE*, are an example of students' inability to associate this word with the topic under study. Instead, students reported to the common meaning of this word and made the association with daily words in the following manner: "*RESISTANCE* is a barrier that *stops*".

Regarding the connections made between the words *ELECTRIC CURRENT* and *Energy*, they reveal that most students understand that there is some relationship between them, although they do not explain it: "The *ELECTRIC CURRENT* relates to the *energy* we have at home and at school". Furthermore, the results also show that some students have alternative conceptions about the relationship between these two concepts. In the statement "The *ELECTRIC CURRENT* decreases as *energy* is consumed" is notorious the confusion between *ELECTRIC CURRENT* and (electric) *Energy*. This is a common alternative conception that justifies another frequent alternative conception: the perception that students have that electric current is consumed. According to Tsai et al. (2007), based on a national study involving more than 10,000 students (grades 8, 9, and 11) students not only have difficulty in differentiating between electric current and energy, but also reveal ideas according to the current consumption model, according to which the current is consumed by, for example, a lamp.

The stimulus word *VOLTAGE* was associated with the word *Danger* because, according to them, "The *VOLTAGE* poses a *danger* of death", an idea identical to that they have concerning the electric current. In addition, it is possible to verify that some response words associated with electric current are also associated with the word *VOLTAGE*, which is indicative that electric current and voltage are seen as being similar. In fact, the misunderstanding between several concepts (electricity, electric current, electricity, power, voltage, charge, etc.) is described in the literature by several authors (Çepni & Keleş, 2006; Shipstone, 1988; Tsai et al., 2007; Turgut et al., 2011).

Finally, at the last level, for both groups, appears the last stimulus word (*BATTERY*), which, according to the students "(…) gives constant *energy* to toys" and "*BATTERY energy* is consumed for the flashlight to give *light*". Once again, these results, namely the one related to the role of the battery, are in accordance with what is previously reported, and that indicates that students tend to assume that a battery is a source of constant current (Afra et al., 2009) or constant energy (Turgut et al., 2011). Additionally, in a more recent study, Preston et al. (2020) performed a 2-year longitudinal study with Year 6 classes that aimed to explore issues of teaching the topic of electricity through a Representation Construction Approach (RCA), like the students' outcomes. Student-centered and inquiry-based approach activities were implemented and one of the findings, regarding the role of a battery, was that most of the students had an erroneous pre-instructional view: 44% of the students thought that the battery stores electricity, or power (13%). Furthermore, following the topic, although 74% of the students indicated the correct answer (energy), there were still some students that maintained the initial conceptions. The researchers justify these results with the tendency that students have to use these terms interchangeably or to associate electricity with energy.

Still regarding M1, the maps of students' cognitive structures at this moment allow to recognize the existence of an isolated island for the word *RESISTANCE*, which makes it difficult for students to mobilize the knowledge concerning this concept (Cardellini & Bahar, 2000). Also, the fact that the other stimulus words are indirectly associated (i.e., they are associated through response words) reveals that students do not possess a full dynamic conceptual network that allows them to move directly from one concept to another and, consequently, to easily solve complex problems (Cardellini & Bahar, 2000).

RQ2: What is the effect of a STEM approach on the development of students' cognitive structures, and consequently on their conceptions, on the topic of electrical circuits?

In what concerns the second investigation question, it is possible to verify that the cognitive structures of the students belonging to the experimental group were different from the ones of the control group, which indicates that the different learning sequences had different effects on students' outcomes.

Specifically, and by comparison of the maps at M2 (Figs. 3 and 4), two aspects stand out: the number of levels and the complexity of the maps. As for the number of levels, the fact that the map of the cognitive structures of the control group has five levels and that of the experimental group has four levels is indicative that the strength of the associations is greater in the experimental group, with the stimulus words appearing at higher frequencies. While in Level 4 ($120 > f \geq 80$) of the experimental group all the words stimulus are presented in the cognitive structures of the students, in the control group, the last stimulus word only appears at frequencies below 80.

Regarding the complexity of the maps, it is possible to verify that the map relative to the experimental group (Fig. 4), at Level 4, is characterized by a denser and more intricate network (i.e., with more associations) than the map of the cognitive structures of the control group (Fig. 3).

Another aspect that distinguishes the students' maps of cognitive structures of the two groups is the quality of the words associated with the stimulus words. We perceive quality as being associated with the nature of the words. Response words that are unequivocally related to curricular contents were considered as having higher quality than words related to everyday situations. Thus, in general, in the control group, most of the associations that students made are related to everyday situations, while in the experimental group, students made many associations related to the curricular contents. For instance, in the control group students do not possess, in their cognitive structures, any word regarding measurement devices (*Ammeter*, *Voltmeter*) or SI units (*Ampere*, *Ohm*, *Volt*). Another word that is not present in the cognitive structures of students from the control group is the word *Electrons*. However, students from the experimental group associated the word *Electrons* with, for example, *ELECTRIC CURRENT* in the following way: "*Electricity* is the *ELECTRIC CURRENT* that is due to the movement of the *electrons* in the circuit".

Furthermore, in some cases where students in the control group made identical associations to those in the experimental group, related to curricular content, the nature of the associations is different. For example, the stimulus word *VOLTAGE* appears, in the experimental group, associated with words such as *Electric circuit*, *Volt*, *Voltmeter,* and *Electrons*, while in the control group it continues to be essentially associated with words related to everyday life, such as *Home appliances*, *Electric shock*, *Electricity*, etc. Examples of sentences written by the students of the experimental group include "The *BATTERY* in the *electrical circuit* creates a *VOLTAGE*" and "The *electrons* remain in the *circuit* and are oriented because of the *VOLTAGE*", which is indicative of the understanding, in this case, of the concept of voltage. Still regarding the stimulus word *VOLTAGE*, and although both groups have made associations with the word *Electric circuit*, their nature is different: in the experimental group, students refer that "The *BATTERY* in the *electrical circuit* creates a *VOLTAGE*", while in the control group the students only state that "The *electrical circuit* has a *VOLTAGE*".

Also, the associations made with the word *BATTERY* are different in the two groups. Students in the control group continue to associate this word with *Stop*, stating that "*RESISTANCE* is for *electricity* to *stop*", while in the experimental group students already associate it with words such as *Ohm* and *BATTERY* in the following ways: "*Ohm* is the name of the one who invented the law and is the unit of *RESISTANCE*" and "*RESISTANCE* can be a component of the *circuit* that is connected to a *BATTERY*".

Regarding the alternative conceptions identified at M1, for both groups, they were observable at lower percentages, at M2, and were not the most prevalent ideas in students' cognitive structures, as it happened before instruction. Furthermore, it was in the experimental group that it was verified major differences in the elimination of alternative conceptions. Specifically, in the control group, the percentage of associations that were considered alternative conceptions shifted from 61,3% (M1) to 38,7% (M2). However, in the experimental group, this variation was more pronounced: from 62,9% (M1) to 18,5% (M2).

Considering the mentioned features, it is possible to conclude that there are more differences between the cognitive structures' maps of the experimental group, considering both moments, than of the control group. This is indicative that the student-centered STEM approach had a more pronounced effect is students' cognitive structures.

Conclusions

The findings of the current study indicate that the STEM approach had a more pronounced effect on the development of students' cognitive structures on the topic of electrical circuits, which reinforces the research in STEM education, by describing a pedagogical approach that allows students to achieve the learning goals, in comparison to the traditional pedagogical approach. Furthermore, WAT has proven to be a suitable method to elicit about students' conceptions. Thus, it can be used by teachers to identify students' conceptions and difficulties, and to select proper pedagogical experiences that help students to learn. Also, it can be used to evaluate the accomplishment of students' learning objectives. As such, this instrument can be used in the classrooms, regardless of the subject/topic to inform teachers about the "starting point" of the class. For teachers, it is a powerful tool to know what their students know and think about a topic. Despite the complex and time-consuming data analysis, WAT data can guide teachers to adapt their pedagogical approaches and to help students in their learning process. Other WAT modalities include the comparison of students' cognitive structures before and after instruction, or the comparison between different approaches, to decide which is the most effective. WAT can be also used in conjunction with other tools. For instance, teachers can perform an initial WAT and, instead of performing a post-instructional WAT, they can ask students to build concept maps.

The main limitation of the present study is the utilization of a group analysis, instead of an individual analysis. This means that WAT results were analyzed considering groups of students (control and experimental), instead of individual students. Therefore, it does not allow the assessment of individual cognitive structures but only the determination of the most prevalent associations and directions of such associations within the students' groups under consideration.

Another limitation is the fact that this study was conducted in only 12 Portuguese schools and the recruitment of participants was made by a convenience sampling method which introduces some precautions in the generalization of the results.

Despite these limitations, this study provides general trends among students' conceptual understanding of electrical circuits and related concepts and opens the door for further research.

Abbreviations

STEM	Science, Technology, Engineering, and Mathematics
WAT	Word Association Test

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Both authors conceptualized the study and were involved in data collection and analyses. Both authors read and approved the final manuscript.

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Availability of data and materials
The datasets generated and/or analyzed during the current study are not publicly available due to the anonymity and the confidentiality of the collected data but are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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