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Research Article

Physics teachers' learning on the use of multiple representations in lesson study about Ohm's law

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ABSTRACT

The article analyses teachers' learning on the use of multiple representations (MRs) in the teaching of Ohm's law, examining them in a lesson study, structured in 18 meetings of 2.5 hours each, that addressed this physics curricular topic for the 3rd grade of high school. The qualitative research involved four teachers who teach physics in Brazilian public schools. The empirical material of the study consists of the transcriptions of the audio recordings of the lesson study sessions, interviews with the teachers at the end of the process, and students' written registers produced during the class. From the participating teachers' perspective, the analysis showed that the emphasis on MRs improved the teaching of Ohm's law because it helped them obtain complementary information - to correlate the different representations; acquire a fuller and deeper understanding of the physics concept; connect the abstract to the concrete - carry out constraint interpretations – interpreting the physical concept by familiarity and inherent properties, and interpreting and transposing representations; construct in-depth understandings – interpretations and relationships between tables, graphs and generalization of equations; and develop investigative activities encompassing abstraction, extension, and the relationship between physical quantities. Considering the complexities of MRs, teachers examined what information is actually accessible to students and how they can use it, encouraging them to seek an effective way to integrate several representations to assist in the learning process.

Keywords: multiple representations, teacher learning, Ohm's law, lesson study

INTRODUCTION

Professional learning is a dynamic, permanent, personal, and socially constituted phenomenon in the interaction between teachers through the confrontation and modification of ideas and the reinterpretation of their experiences (Flores, 2004). Such learning is related to the disciplinary field, teaching in the classroom, aspects of teaching management, elements of the professional context, students' learning processes and their learning difficulties, and social and cultural elements of the professional context, among other processes intrinsic to teaching (Richit & Tomkelski, 2020). In this way, the collective work on specific situations of the curriculum component and the didactic issues expand teachers' professional knowledge (Ribeiro & Ponte, 2019), providing learning of a different nature.

Through professional learning, teachers can analyze and understand issues related to teaching and propose changes in practice. For example, physics teaching in high school imposes distinct challenges on the teacher, mainly due to difficulties in learning concepts and their representations and solving problems involving physical concepts. These challenges require curriculum and didactic decisions that presuppose a teacher's professional learning, such as on multiple representations (MRs).

The theme of multiple representations has aroused the interest of teachers and researchers in mathematics and natural sciences, especially physics, due to the possibilities of addressing curricular topics and favouring the understanding of specific knowledge in these areas. In the context of the didactic of the sciences, MRs characterize the different ways of representing a concept or phenomenon under study, which may be internal or external. External representations are expressed, explained, through symbols, graphs, tables, figures, and virtual simulations, while internal representations consist of mental representations (Opfermann et al., 2017).

Classroom investigations have emphasized that teachers do not always use MRs to help students understand scientific concepts (Ainsworth, 2008). So, to help teachers learn to use MRs in physics teaching, there must be formative (initial, continuing, and in-service) processes (Nieminen et al., 2017) through which teachers can explore properties and relationships of specific curricular topics and ways of teaching them in the classroom. Teacher education centred on practice provides opportunities for creating a favourable context for the generation of teachers' professional learning (Ribeiro & Ponte, 2019).

The *lesson study* is one of the formative approaches that contemplate those aspects, increasingly used in teachers' initial and continuing education in different areas of knowledge. It aims to favour the teachers' professional development in their different dimensions (Richit, 2021). Originally from Japan, lesson study features a teacher professional development approach focused on teaching practice and supported by two fundamental principles: collaboration and reflection (Richit et al., 2020). By focusing on teaching practice, the lesson study has supported investigations on aspects of learning various curriculum topics, such as MRs and their role in science learning. In this sense, lesson study, by its nature and characteristics, constitutes a context for the accomplishment of changes in physics teaching (Conceição et al., 2016), as they provide classroom approaches that promote the mobilization, exploration, and articulation of MRs, contributing to student learning.

Investigations into lesson study as a formative process for physics teachers have shown promising results (for example, Baptista et al., 2020; Juhler, 2018; Tomkelski et al., 2022; Zhou et al., 2016), but there are still few investigations in lesson studies with teachers in the areas of the natural sciences, especially on the use of MRs in physics teaching (for example, Baptista et al., 2020; Conceição et al., 2021). In addition, much of the research on lesson studies involves initial teacher education in mathematics, and fewer studies address physics (for example, Conceição et al., 2016; Pektas, 2014; Rodrigues & Arroio, 2020). Moreover, investigations involving lesson study as a process of professional development of basic education teachers carried out in Brazil are focused on mathematics teacher education (for example, Richit & Tomkelski, 2022; Richit et al., 2019; Rincón & Fiorentini, 2017; Wanderley & Souza, 2020) and few in physics (e.g., Rodrigues & Arroio, 2020; Tomkelski et al., 2022).

Instigated by the possibilities of MRs in physics teaching, we carried out an investigation involving four physics teachers in a lesson study. Based on the pedagogical content knowledge (PCK) perspective presented by Shulman (1986, 1987), we analyzed teachers' learning about the use of MRs for teaching Ohm's law, guided by the question "What professional learning do physics teachers acquire in a lesson study on Ohm's law?" Ohm's law states that the electric current flowing through a conductor is proportional to the voltage applied at its terminals. By associating three physical magnitudes, Ohm's law shows how the voltage, electric current, and electrical resistance magnitudes are related.

The lesson study focused on deepening the topic of Ohm's law because, as the participating teachers taught in the 3rd grade of high school, they immediately suggested that the topic be related to electricity. In the negotiation process and definition of the topic to be deepened, the group opted for Ohm's law because students generally find it hard to grasp this concept, associating it only to the equation that represents it.

Ohm's law is a fundamental curricular topic in electricity studies, especially electrodynamics, constituting a concept of the relationship between the physical magnitudes of voltage, intensity of electric current, and electrical resistance, and the understanding of the other elements present in electrical circuits. Ohm's law is a basic principle in the operation of several electrical components. Resistors, for example, are part of circuits that consume electrical energy and convert it into thermal energy. Therefore, this law is an essential topic since many of our daily activities depend on the use of electrical energy and electrical devices. We found several examples of use for lighting purposes (cities, homes), for heating (electric showers, heaters, microwaves), and the various models of electronics (TVs, cell phones, computers) and home appliances. In addition to resistors, electrical circuits have other components, such as generators and receivers; however, these components were not analyzed in this specific curricular topic.

The topic allows students to learn about the proportionality relationships between the magnitudes and understand how electrical charges act in the transport of electrical energy, passing through generation (generators) and dissipation (receivers). According to the participating teachers, in the learning process, students usually have difficulties in conceptually differentiating physical magnitudes and the relationship between them, often caused by misunderstandings of the task statement.

MULTIPLE REPRESENTATIONS IN PHYSICS TEACHING

In science, human knowledge is developed through representations (Wartofsky, 1979). Thus, certain information is better represented in a particular way, while others are better understood when they resort to different representation strategies, for example, when using MRs.

Treagust and Tsui (2013) point out that the term "multiple" directs to several dimensions, such as different modes of representation, different degrees of abstraction (such as physical objects, photos, diagrams, graphics, text), different scopes or level of representation (such as macro, micro, sub-micro, and symbolic) and different topics or domains of content (ecology, energy, evolution). Thus, resorting to various representations allows us to correlate various aspects of a phenomenon, build a complete and deep understanding of science, and assist in effectively communicating scientific concepts (Ainsworth et al., 2011).

In this perspective, multiple representation or multimodal representation is understood as the integration of different ways of representing reasoning, processes, and scientific discoveries, aiming that students appropriate the meanings of concepts to the extent that they gradually master the different ways of representing discourses (Tytler et al., 2007), ideas, or concepts. In physics teaching, especially, MRs converge and reinforce the conception that they allow a clearer and more integral conceptualization of scientific concepts, facilitating their understanding and communication (Opfermann et al., 2017). They also promote students' interest in learning sciences, as they allow connecting the abstract to the concrete (Park et al., 2015), favoring the connection with MRs and with the understanding of the phenomena of the reality that surrounds us, making up a fundamental part of the nature of science (Erduran & Dagher, 2014). Therefore, MRs constitute an excellent opportunity for students to learn science, especially physics (Opfermann et al., 2017).

Ainsworth (1999, 2006, 2008) conducted a conceptual analysis of MRs learning environments and suggested a taxonomy of three main functions of MRs: obtaining *complementary information*, performing *constraint interpretation*, and building *in-depth understandings* of the topic under study. Each of the functions can be subdivided into several subclasses, and often a single representation environment can serve several of the functions shown, but each class will be considered separately.

Figure 1 summarises MRs functions. In complementary information, different processes are involved, allowing us to obtain different information based on strategy, individual differences, and tasks about the investigated topic, supporting complementary cognitive processes. The constraint interpretation function relates the different representations by familiarity or inherent properties, making it accessible to students. In the function of in-depth understanding, there is a conceptual deepening that goes through abstraction, extension, and relation, boosting the learning process.

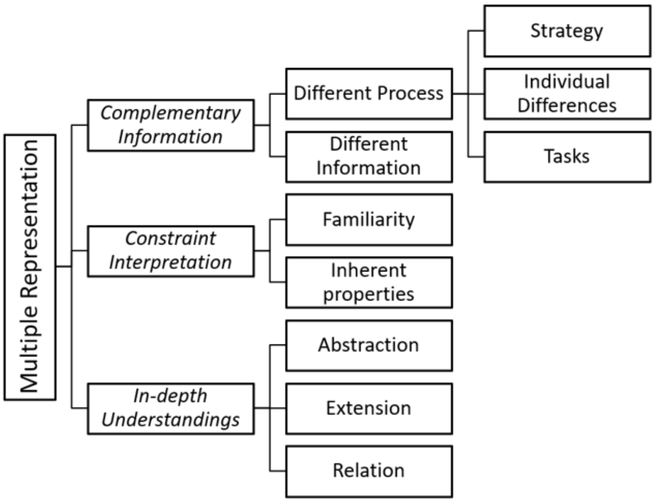

Figure 1. Functions of multiple representations (Adapted from Ainsworth, 1999, 2006, 2008)

The first function concerns using representations that cover *complementary information* or that support complementary cognitive processes. It consists of providing complementary information about a concept, facilitating its learning; for example, a table explains the information, allowing values, regularities, and patterns to be highlighted (Ainsworth, 2008) or a graph that allows visualizing relationships between variables (Chittleborough & Treagust, 2008).

In the second function, *constraint interpretation*, a representation is employed to restrict possible (re)interpretations using another. For example, a specific representation constitutes a starting point to encourage students to interpret a complex representation by familiarity with a simpler representation (Ainsworth, 2008). A table, for example, is usually more familiar to students and can help them to interpret a graph (Ainsworth, 2014). Another way is to encourage students to take advantage of the properties of each representation of a problem or phenomenon. For example, an algebraic equation allows the student to establish quantitative relationships between variables and manipulate them numerically; however, because it has a high degree of abstraction, this representation is not always accessible to students. Nevertheless, starting with the relationship of variables graphically can be a strategy to mobilize students to interpret the algebraic equation that involves these variables (Ainsworth, 2014).

Also, in this function, MRs can encourage students to use a given representation by familiarity and, concomitantly, by their properties, such as, for example, using a table to help students interpret a graph and analyze the relationship between the magnitudes involved. In this situation, the table is used by familiarity because it is usually near to students and, simultaneously, by its properties of explaining the information, making it accessible to students (Baptista et al., 2020).

In the third function, *in-depth understanding*, MRs drive students to build a deeper understanding of a given situation (Ainsworth, 2008). They can do it by abstraction – for example, the students' generalization of a given concept arises from what they learned in a particular context and with MRs values, or can do it by extension – for example, students use the application of previous learning to achieve new representations or can obtain them by relationship, building relationships between representations (Baptista et al., 2020). In practice, in science teaching, specifically in physics teaching, this is equivalent to providing students with the opportunity to have contact with the most different modes of representation, whether verbal, graphic, tabular, figurative, diagrammatic, photographic, analogical, metaphorical, kinesthetic such as experiments, (3-D) models, gestures, mathematicians, and filmic representations among others (Laburú et al., 2013).

Considering the complexity of MRs, investigations have highlighted that it is the teachers' responsibility to examine the information that actually becomes accessible to students and how they can use it and then find the best way to integrate several representations to assist in the learning processes (Prain et al., 2009; Wu et al., 2013). Thus, using different representation processes constitutes favorable strategy for physics learning (Baptista et al., 2020). Therefore, MRs provide opportunities for changes in the physics teaching and learning processes because in science, as in much of art, human knowledge is ascended through representations (Wartofsky, 1979).

In Brazil, MRs are referenced in the basic education guiding documents to include the proposed objectives for teaching the sciences. According to the national curriculum guidelines for science teaching, MRs refer to the development and use of tools, including digital ones, in the collection, analysis, and representation of data (images, schemes, tables, graphs, charts, diagrams, maps, models, system representations, flowcharts, conceptual maps, simulations, applications) (Brasil, 2018). Given these aspects, we emphasize the relevance of this investigation because it allows us to better understand the contributions of MRs to the learning of Ohm's law.

LESSON STUDY

Lesson study, *kenkyuu jugyou* in Japanese (Lewis, 2000), is a teacher professional development approach widely used in Japan and is considered the main responsible for the improvement of teaching in that country (Richit & Tomkelski, 2020; Yoshida, 1999). One of the main characteristics of the lesson study is that it consists of a work that a group of teachers develops collaboratively (Fernandez & Yoshida, 2004; Lewis, 2000, 2009; Lewis & Tsuchida, 1998; Stigler & Hiebert, 1999; Yoshida, 1999), favoring professional learning, especially on topics of curricular content and ways of teaching them in the classroom (Lewis, 2016; Murata, 2011). Due to the characteristics of this model, teachers develop in-depth knowledge about the topic, its teaching, and students' learning (Stigler & Hiebert, 1999).

In Japan, lesson study has a central structure constituted of four moments: identification of a *context* and definition of a *goal* for the development of the research lesson; *planning* in which a group of teachers work collaboratively over several sessions to plan a lesson on a specific curriculum topic; a *research lesson*, which is developed in a group of students; and *post-lesson reflection*, when the group meets to discuss and reflect on the students' actions in the investigative lesson, considering the aspects registered by the observers (Richit, 2021; Richit et al., 2019). The cycle can be repeated, deepening the study on a given content or starting again for new content (Fujii, 2016). **Figure 2** presents the lesson study cycle constituted by four moments.

Figure 2. Lesson study cycle of the investigation (Tomkelski et al., 2022)

The lesson study promotes formative situations for teachers, focusing on preparing a task on a given topic, planning the class with this task, observing the execution of the class and post-lesson reflection to discuss the teaching of the topic based on the students' results (Fujii, 2016; Murata, 2011). Therefore, from the stages of lesson *planning*, *research lesson*, and *post-lesson reflection*, the lesson study systematically incorporates the teachers' professional development in the classroom, anchored in the idea that a single class contains many (if not all) critical components that teachers must consider to improve their education (Sims & Walsh, 2009).

As an example, in Baptista et al.'s (2020) research, teachers used MRs in teaching the kinetic energy of a body in a lesson study context and concluded that teachers should learn how to use MRs for the understanding and communication of scientific concepts (Ainsworth, 2008, 2014; Nieminen et al., 2017). The research also points out the need to create formative situations that help teachers in the use and exploration of the potential of MRs in teaching physics concepts (Baptista et al., 2020).

METHODOLOGY

General Background

This investigation followed the qualitative perspective of the research, whose specificity is related to how problems involving the content are addressed, leading the researcher to seek methods that will be appropriate for the study of this content. It also includes careful registers in writing and other types of documentary evidence (field notes, memos, student work, audio recording, video recording) of everything that happens during the observation process, the subsequent analytical reflection on the documentary record, and the reports through a detailed description (Erickson, 2012). Therefore, the qualitative and interpretive analysis method is beneficial in understanding teachers' learning about the use of MRs in a classroom context.

Participants

The lesson study involved four physics teachers of the 3rd grade of high school in public schools in Rio Grande do Sul (RS), Brazil, in the region covered by the 15th Regional Coordination of Education (CRE), based in Erechim. The selection of participants was made possible by invitation or convenience, for example, proximity to the researcher.

The participants, Sol, Jô, Mel, and Roberta1–fictitious names (**Table 1**), aged between 38 and 52, teach exclusively in the public school system of the state of RS. The participants have between eight and 25 years of professional experience in basic education2, specifically in elementary school and high school, and most attended a specialization course.

Table 1. Characterization of the participants

Participant	Age (years)	Education	Professional background	Professional experience
Jô (J)	38	Degree in mathematics–qualification in physics [Especialisation (lato sensu)]	Teaches physics & mathematics in basic education (elementary & high school) & EJA	18 years
Mel (M)	52	Degree in mathematics–qualification in physics [Especialisation (lato sensu)]	Teaches physics & mathematics in basic education (elementary & high school) & EJA	25 years
Roberta (R)	45	Degree in mathematics–qualification in physics [Especialisation (lato sensu)] Master's degree in mathematics & physics teaching	Teaches physics & mathematics in basic education (elementary & high school)	13 years
Sol (S)	39	Degree in mathematics–qualification in physics [Especialisation (lato sensu)]	Teaches physics & mathematics in basic education (elementary & high school) & EJA	8 years

Organization of the Lesson Study

The lesson study was composed of eighteen sessions of two and a half hours each, divided into five stages:

(1) theoretical constitution of the approach to lesson studies and analysis of the legal documents of the current Brazilian educational legislation,

(2) analysis of research tasks for the classroom,

(3) planning work for the first lesson addressing the investigation, reflections about, and refinement of the activity,

(4) conduction of the first research lesson in the classroom, post-lesson reflections, and review of the work plan, and

(5) conduction of the second research lesson, post-lesson reflection, and end-of-the-work plan.

Fifteen sessions took place on the premises of the 15th CRE, based in Erechim, RS, Brazil, two sessions took place at the Escola Estadual de Ensino Médio São José, Ponte Preta, RS –application of the diagnosis of investigative tasks and second investigative lesson– and one session was held at Escola Estadual de Ensino Médio Professor João Germano Imlau, Erechim, RS –first investigative lesson. In the two investigative lessons, the teachers (first, Jô and then Sol) focused on the same physics topic. Each class lasted 100 minutes.

Instruments and Procedures

The empirical material consists of the data collected throughout the formative process, including *logbook* (*LB*); *audio and/or video recordings* (*AVR*) and transcripts; *documentary collection* (*DC*) of teachers' written productions and also the students' registers produced during the investigative lesson; and *interviews* (*I*) with the teachers. The sessions were observed by the researcher, who adopted an observer-as-a-participant role because he intended to obtain detailed information about the process (Cohen et al., 2011).

The field notes are the registers of ideas, strategies, reflections, and opinions. The patterns that emerge from the study are always based on detailed, accurate, and extensive notes (Bogdan & Biklen, 1994), which were systematized in the reports produced after each session. The interviews conducted after the end of the lesson study were transcribed and put into writing and then incorporated into the empirical material of the investigation. We also incorporated into the empirical material the documents produced by the teachers during the lesson study, such as activity resolutions, representations, materials from classroom intervention, and the logbook in which the participants registered their impressions and reflections at each meeting.

Data Analysis

The analysis highlighted aspects of Ainsworth's taxonomy of MRs functions (1999, 2006, 2008). The analysis categories that emerged from the data, according to the content analysis (Bardin, 2011), ended up also converging with MRs functions and were regrouped into three main categories:

(i) complementary function,

(ii) interpretation constraint, and

(iii) in-depth understandings.

After, each category was structured into subcategories organized, as follows:

(i) considering the different information and different process (strategy/individual differences/tasks) of MRs,

(ii) considering the interpretations by familiarity and inherent properties, and

(iii) considering the processes of abstraction, extension, and ratio.

In this way, the categories of analysis were constituted from content analysis (Bardin, 2011), based on Ainsworth's (1999, 2006, 2008) perspective of MRs functions. Each function corresponds to a category of analysis. Moreover, each category relies on subcategories, depending on the specific role of MRs in teaching the topic 'Ohm's law' (**Table 2**).

Table 2. Categories & subcategories of analysis of teachers' learning in the use of multiple representation

Category	Subcategories
Complementary function	– MRs as different information – MRs as a different process (strategy/individual differences/tasks)
Constraint interpretation	– MRs by familiarity – MRs by inherent properties
In-depth understandings	– MRs by abstraction – MRs by extension – MRs by ratio

The results were grouped into the corresponding categories and subcategories, and the data were difficult to categorize, being discussed among the authors to reach a consensus. The non-consensual data were not used.

RESULTS

The analysis, supported by Shulman's PCK (1986, 1987), showed teachers' learning using MRs in Ohm's law teaching. Defined a priori from the perspective of Ainsworth's (1999, 2006, 2008) MRs functions, the categories are complementary, constraint interpretations, and deep understanding. Each category is discussed from the various aspects related to the use of MRs in the teaching of Ohm's law, evidenced in the analysis of the empirical material. These aspects are called subcategories.

Complementary Function

During the planning phase of the research lesson, the teachers discussed the use and contributions of MRs in teaching Ohm's law, highlighting the importance of using *different ways to represent information and also for their learning* as teachers. From delving into Ohm's law by exploring MRs, the teachers considered that MRs use contributes to obtaining the best student learning results. Roberta emphasizes this aspect by pointing out that

> R: One way that has shown to be efficient in learning science teaching is through representations. Provide students with activities on the most diverse types of representations: verbal, graphic, tabular, diagrammatic, photographic, models, experiences, algebraic, etc. (LB).

By emphasizing the representations, naming the verbal, graphic, tabular, diagrammatic, photographic, models, experiences, algebraic, and other representations, Roberta highlights the possibilities of analysis that can be explored in the development of the investigation task in obtaining the relationship between the physical magnitudes, in this case, the difference in electric potential (U) and intensity of the electric current (i), converging to the understanding of Ohm's law. That is, the use of information presented in different ways helps in the representation process and, consequently, can improve physics learning, specifically Ohm's law, to the extent that the concept of electrical resistance (R) can be obtained from different sources of information (experience, tabular, graphic, verbal) to obtain the mathematical relationship between the physical magnitudes (R=U/i).

During the study of Ohm's law, the teachers' learning in the complementary function of MRs marked different moments in the lesson study, of which we mention one of the class planning sessions in the context of the discussion of one of the activities. In the discussion, we noticed that teachers appropriate the *different information* and *processes that MRs enabled*, anticipating the students' probable learning and, mainly, their conceptual learning.

> M: Analyze the questions, because then, I think we will learn better how to work with the various representations [...].
>
> R: So, this first representation, is it a restrictive representation? Restrictive or construction?
>
> J: It is a comparison because, to determine the number of conductors, the resistance value remains constant, it does not depend on the voltage. So, when the conductor is Ohmic, will this always happen?
>
> J: Yes! In this case, we started with a small voltage and then increased it. And we established those comparisons and relationships because it is gradually increasing there [...] even if I take the last magnitude with the first, or the third with the first, that there will always be proportionality.
>
> M: By the graph, when the voltage increases, the current increases in the same proportion, so the graph is a straight line!
>
> S: Uhum. The higher the current, the higher the voltage and the resistance remains the same, and it will be a cycle [...]. That is why we say constant of proportionality.
>
> J: We are comparing too, when you increase one, the other increases, but the resistance is constant.
>
> R: Then the graphs are saying what an Ohmic conductor is and what is not an Ohmic conductor, because the graph will be a constant, a straight line; and then what is not, will not be a straight line.
>
> S: With the graph, we are interpreting the inherent properties.
>
> Jô: So, when it does not obey the law, the resistance is no longer constant, so, this is a property that we are evaluating of the resistance being Ohmic or not.

> M: That's right, by looking at the graph or putting this data in a table, you can see when the ratio is maintained or when it is changed. When it is maintained, it is in accordance with Ohm's law, right?
>
> J: It obeys Ohm's law because R is constant, constant of proportionality!
>
> M: That's interesting, because now, I could expand my concept. At first, I had understood that I always had to divide the voltage by the current, punctually. But now I realized that if I also take the variation between two points and I make this division, this proportionality, too, remains. For me, this is a conceptual leap (AVR).

Regarding the use of different representation processes, Jô highlights its importance in teachers' professional development when she says that

> J: This kind of information [...] makes it much easier for us to understand [...] because we have an extra tool to demonstrate [something] to our students. So, all that we used, those MRs, we colleagues used, in a way, used one of them. Not all of them, of course! (I).

The teacher emphasizes the importance of MRs in physics teaching, arguing that the use of various representations corroborates the development of planning and action in the classroom. The teachers also emphasize that teachers usually use only one form of representation. Thus, they conclude that the learning actualized in the lesson study allowed them to develop theoretical elements that facilitate the expansion, diversification, and articulation of the different representation processes in the development of activities, learning strategies, and analysis of the specificities of different topics of physics, especially in the development of the Ohm's law topic.

Constraint Interpretation

Regarding the constraint interpretation, the analysis showed that the teachers frequently reported students' difficulties, along with their own difficulties regarding Ohm's law or involving MRs. They also expressed concern about the transition between the various forms of representation and brought ideas for developing the research lesson, as they were not used to exploring different representations in the classroom. Sol says:

> S: What we find most difficult as teachers, and they do too [*referring to the students*], is the issue of the graph! It is the question of interpretation, transposing, understanding what the figure is, because it follows a pattern, because it does not follow [it], this is the greatest difficulty to pass on to them (I).

Sol emphasizes that the difficulty in the transition between the different forms of representations, especially from the graph to other forms of representation, stands out in relation to the theoretical content of Ohm's law due to the teachers' lack of sufficient skills and knowledge to assist students in this learning process. Thus, it seems that, due to these limitations, teachers often do not explore the transition between MRs with students, limiting themselves to more simplistic content analysis based on a single representation.

Given this discussion, the teachers suggested exploring, in the research lesson, other forms of representation *based on the representations students already know*, i.e., using familiar representations and expanding to others. In this sense, they proposed an investigative activity to explore different representations.

> M: [The] task, [we should] organize it in such a way as to lead students to make this transition, according to the topic, from making the transition from one to the other, then to the other, and, in the end, try to get those representations [referring to the Ohm's law equation]. This activity would be complete: it would have complementary information to interpret, compare, and evaluate, and each one; they are different processes, or contents, if that is the question of familiarity or inherent properties; if this construction generated an abstraction, an extension, or just a relationship (DC).

Mel emphasizes the importance of developing activities that instigate students to move between the various forms of representations, establishing relationships, learning from them, and directing the generalization, which is the following function of MRs. They concluded that exploring these different representations and the opportunity to move between them allows students to develop the necessary functions to learn other physics topics, such as Ohm's law. Later on, Mel complements this aspect by proposing suggestions to develop the research task, which permeates the understanding of Ohm's law through MRs.

> M: The task could cite an example of an Ohmic conductor, bringing part of the values, then we build a table, build a graph. And students will acknowledge the relationships [familiarity] and draw conclusions from the information contained [inherent properties] (AVR).

By detailing the characteristics and structure of the investigative task to address Ohm's law, the teacher proposed an activity that involved measurements of the difference in electric potential (U) and intensity of the electric current (i). Mel suggested that some measurements be given and, from the relationship between them, students could complete the other measurements in a table. Then, they would represent this data graphically. And in doing so, they would identify the regularity between the corresponding measurements, thus understanding Ohm's law. This detailing ascertains the learning involving the potential for MRs exploration in the study of this topic to improve students' learning, covering the subcategories of interpretation by familiarity.

Mel's suggestion became a reference for developing the research lesson, which was organized into two investigative activities to explore various forms of representations, especially the *properties inherent to the concept*. This aspect was highlighted by Jô:

> J: We used in class preparation graphs, tables, formulas [proportional relationship between quantities], diagrams [pictorial], experiments [practical activity] and written explanations [text]. Thus, several representations, several MRs in our [school] context (I).

Thus, the first activity involved a situation that instigated students to propose a pictorial representation of the electric circuit and, later, a representation using the classical elements of physics. Subsequently, they performed a concrete, practical experiment involving batteries, wires, LED lamps (light emitting diode) and measuring instruments (multimeter). After measuring and systematizing the results in a table, the students plotted the corresponding graphs and performed analyses in search of proportionality patterns, ending with a first attempt to generalize Ohm's law, without, however, using the symbology of physics, that is, R; U or i. For the first activity, the group decided to consider an Ohmic conductor. The second investigative activity adopted a similar approach but focused on a non-Ohmic conductor, as Mel detailed

> M: [For the second activity] we changed the logic. [We] start from another, more concrete situation, of a non-Ohmic conductor. [From this, the student] simulates values, builds the table and makes a graph with those values. [We ask] them to systematize in a table, and later to get the representation in the law; what if we did an activity with two graphs a and b? At last, you get those representations. And finally, it ends, then, with the generic graph, making the relationship, extension, and abstraction with the formula (AVR).

This idea was complemented by Roberta, who added a more in-depth analysis of the relationship between Ohmic and non-Ohmic circuits by suggesting,

> R: Why don't we think, then, about an Ohmic and non-Ohmic graph at the same time? In that at some point it is Ohmic, to some point it is Ohmic, therefore, it agrees with the relationship; but after a certain moment, it is no longer Ohmic (AVR).

Thus, the second activity began with a text on Ohm's law and continued with the analysis of a graph with some values given and others estimable, directing the transposition of these data in a table or other form of *familiar representation* to the student. Next, the data in the table were analyzed, seeking patterns of proportionality. Subsequently, from a hypothetical situation, the task presents a table with three distinct situations, two Ohmic and one non-Ohmic conductors, that were transposed to graphs and analyzed individually and collectively.

Finally, the activities directed the students to generalize the Ohm's law equation, i.e., to obtain the generalization through the mathematical equation R=U/i.

The development of the activities proposed by the teachers, by involving a concrete context of measurement of electric potential (U) and intensity of the electric current (i), allowed the teachers to explore various forms of representations, moving between the different representations, seeking to lead the students to establish relationships between the systematized measurements and find regularities. In addition, it encouraged teachers to plan activities through which students were instigated to interpret, from a simple to a more complex representation, by familiarity or with other forms of representations, anchored in the properties covered by each activity, directing them to the following function of MRs. Therefore, the teachers could deepen their understanding of Ohm's law by exploring MRs and the transition by familiarity between different representations, as well as the intrinsic properties of this concept, thus making professional learning on the topic and on how to use MRs in physics teaching.

In-Depth Understanding

A deeper understanding of MRs in the teaching of Ohm's law was possible by deepening this topic through the exploration of the different properties and ways of representing this concept, as well as the multimodal transition. This learning was promoted in the planning stage of the activities, post-lesson reflection, and adjustments in the activities for the following research lesson. This aspect was highlighted by Jô when synthesizing the planning and implementation of the research lesson:

> J: We defined the set of activities to be developed: using graphs to demystify the difficulty related to physics; making a relationship with daily life; verifying whether in an Ohmic relationship, it is possible to reverse a graph; concepts; mathematical relationship; MRs; and practice and theory (LB).

Jô also notes the understanding and formation that the teacher needs to be able to assist the student in the development of knowledge about the topic. According to her, MRs

> J: Are fundamental, because they make it easier for us teachers to understand how to put it for the student in a more straightforward and simple way. I think that when [we] use several representations that portray the same information, leading us to the same result, both for us teachers exchanging ideas, it is easier to understand how to pass [the topic] on to the student, and already concerned about the students: "will they understand all this?". Because for us teachers, we, look, analyze: "This is it", but what about our students? Will it be that simple? So, it is essential that we, yes, assess it, that we talk to exchange information with colleagues in the group, it was very important, it added a lot to our classes [referring to the formative process in which she participated] (I).

Jô emphasizes the potential of using the various representations for the teachers' professional development and students' better learning. She also highlights the importance of preliminary analysis and assessment of activities to be developed in the classroom, anticipating students' possible difficulties in understanding and accomplishing what is being proposed. These concerns were expressed by Sol in the post-class reflection session when she analyzed the importance of the insertion of MRs in physics teaching. She pointed out that the students correctly interpreted the statements of the activities and that the exploration of MRs provided them with an in-depth understanding of Ohm's law.

> S: I think there is no way to escape from MRs in physics teaching, mathematics, in short, there is no way to escape, we must use MRs! The group I observed easily reached results in the table, in the drawing, right away, in the circuit design, in the table, and in the graph. For the equation, they took a while, but they also reached it [in reference to the first research lesson]. There [referring to the second research lesson] there were several points that I analyzed, some had difficulties in representing the drawing, others in the table, it is a very heterogeneous class! Then, some reached the result straight away, others found it more challenging, but I noticed a general difficulty with the graph, too (I).

From the observation during the execution of the research lesson, Sol mentioned aspects of students' difficulties and learning, especially when she found that gaps in the learning of fundamental concepts influenced the understanding of the activities; and that previous knowledge was decisive for students' learning success. She observed that in the first activity, the students manifested a little difficulty in the transition of information between tables, graphs, equations, and vice versa, mainly in the construction and interpretation of graphs. However, after exploring these forms of representation and discussing with colleagues in the group about the transposition of the data from the table to the Cartesian plane and, finally, in an attempt to generalize through an equation, students found it easier to perform the second activity, especially moving between representations. This aspect evidenced the teacher's learning about students' difficulties and, especially, about how to promote the exploration of MRs in physics teaching.

Similarly, during the lesson study, the teachers materialize professional learning on the topic by discussing the different resolutions of the activities, going through abstraction, extension, and reaching Ohm's law (equation) relationship.

> S: When the current is zero point one, the voltage is one point five; and in the second, when the current increased to two, the voltage increased, too. Without having a representation, without putting it on the graph, without making them understand what a constant is, what this is, what that is; it would not be possible. So, I think, it is not just put it and play, no! If you're going to play just for the sake of it, there's no point (AVR).

> J: If you increase one, the other also increases proportionally, but to maintain it, to show Ohm's law, the resistance is constant. It replaces the values! In this case, we started with a small voltage, then, it increased. And we established those comparisons and relationships because it is gradually increasing there, which is proportional to that, which will have a coefficient of proportion; even if I take the last magnitude with the first, or the third with the first, that there will always be proportionality (AVR).

By analyzing the proportional relationship between the physical magnitudes of Ohm's law, the teachers achieved a deeper understanding of the topic by extending the proportionality relationship to an entire circuit first and afterwards, generalizing to situations that not only involve the proportion between the values of the potential difference (U) by the intensity of the electric current (i), but that the variation of values (ΔU and Δi) also represents this proportionality. For Mel, if students can reach this level of generalization, there will be a significant "*conceptual leap*" in learning this concept.

> M: Then, that's interesting, because now I could expand my concept. At first, I understood that I always had to divide the voltage by the current, exactly. So, when I have this current, this voltage, I divide; but with this one up here, it leaped, maybe, it should have done the opposite. Here, it shows that if I also take the variation between two points and I make this division, this proportionality, remains, too. For me, this is a conceptual leap (AVR).

In summary, the analysis showed that teachers' involvement in the elaboration of investigative activities on Ohm's law allowed them to deepen their understanding of this concept and propose activities that would allow students to explore MRs with a view to more effective learning. The process, from the planning of the investigative lesson to the post-lesson reflection, evidenced the contributions of MRs to a deeper understanding of a given content, in this case, Ohm's law, insofar as it: permeates the abstraction, extension, and relationship between the physical magnitudes involved. It also revealed the need for clarity of the information presented in the task, avoiding erroneous or biased interpretations and the importance of joint planning among teachers for teachers' professional development.

Table 3 shows a summary of the main aspects highlighted by teachers constituting categories and analysis.

Table 3. Summary of aspects highlighted by teachers regarding the categories of analysis

Subcategory	Teacher' speech
Complementary function	
Different information	- Provide students with activities on the most diverse types of representations: verbal, graphic, tabular, diagrammatic, photographic, models, experiences, algebraic, etc. - Analyze questions, because then, I think we will learn better how to work with various representations. - That's interesting, because now I could expand my concept.
Different process (strategy/individual differences/tasks)	- In this case, we started with a small voltage, then increased it. And we established those comparisons and relationships because it is gradually increasing there. - By the graph, when the voltage increases, the current increases in the same proportion, so the graph is a straight line. - We are comparing too, when you increase one, the other increases, but the resistance is constant. - It obeys Ohm's law because R is constant, constant of proportionality. - But now I realized that if I also take the variation between two points and I make this division, this proportionality, too, remains. For me, this is a conceptual leap. - This kind of information […] makes it much easier for us to understand.
Constraint Interpretation	
Familiarity	- Is the issue of the graph! It is the question of interpretation, transposing, understanding what the figure is, because it follows a pattern, because it does not follow [it]. - [The] task, [we should] organize it in such a way as to lead students to make this transition, according to the topic, from making the transition from one to the other, then to the other, and, in the end, try to get those representations [referring to the Ohm's law equation. - The task could cite an example of an ohmic conductor, bringing part of the values, then we build a table, build a graph.
Inherent properties	- We used in class preparation graphs, tables, formulas [proportional relationship between quantities], diagrams [pictorial], experiments [practical activity] and written explanations [text]. - Start from another, more concrete situation, of a nonohmic conductor […] simulates values, builds the table and makes a graph with those values […] them to systematize in a table, and later to get the representation in the Law. - Students will acknowledge the relationships [familiarity]and draw conclusions from the information contained [inherent properties]. - In that at some point it is ohmic, to some point it is ohmic, therefore, it agrees with the relationship; but after a certain moment, it is no longer ohmic.
In-depth understandings	
Abstraction extension ratio	- Using graphs to demystify the difficulty related to physics; making a relationship with daily life; verifying whether in the ohmic relationship it is possible to reverse a graph; concepts; mathematical relationship; multiple representations; and practice and theory. - They make it easier for us teachers to understand how to put it for the student in a more straightforward and simple way. - Think that when [we] use several representations that portray the same information, leading us to the same result […] it is easier to understand how to pass [the topic] on to the student. - Think there is no way to escape from multiple representations in physics teaching. - Then, some [students] reached the result straight away, others found it more challenging, but what else I noticed was that a general difficulty with the graph. - Without having a representation, without putting it on the graph, without making them understand what a constant is, what this is, what that is; it would not be possible. - We established those comparisons and relationships because it is gradually increasing there; which is proportional to that, which will have a coefficient of proportion; even if I take the last magnitude with the first, or the third with the first, that there will always be proportionality. - It shows that if I also take the variation between two points and I make this division, this proportionality, remains, too. For me, this is a conceptual leap. - Them that's interesting, because now I could expand my concept.

DISCUSSION

The analysis evidenced the contributions of MRs to the study of Ohm's law, based on Ainsworth's (1999, 2006, 2008) taxonomy, in the context of a lesson study. Participation in the lesson study allowed teachers, first, to learn about the functions of MRs and their possibilities and, consequently, to use those functions in planning activities on Ohm's law. Finally, it allowed them to understand how and why students use those functions in their learning.

The results show that the teachers learned to use the three functions of MRs in the study of Ohm's law during the steps of the lesson study. Therefore, they learned to use the complementary function of MRs, encouraging the constraint interpretation of MRs, and to use the in-depth understanding of the physical concepts involved in the study of Ohm's law. Regarding the *complementary function* of MRs, in the planning phase of the lesson study, the teachers suggested using the following representations: text, circuit design, graphs, tables, and equations. The processes of information representation were used as a useful strategy for the classroom (Ainsworth, 2006, 2008), involving theoretical elements that facilitated the expansion, diversification, articulation of the different representations of Ohm's law, which favored the deepening of this concept. The analysis also showed that using a variety of representations helps students correlate various aspects of a phenomenon and build a more complete and deep understanding of the physical concept involved (Ainsworth et al., 2011). It also helps students understand and communicate physical concepts (Opfermann et al., 2017) effectively, allowing them to connect the abstract to the concrete (Park et al., 2015).

Regarding the *constraint interpretation*, the analysis revealed that in the post-class planning and debriefing phase, the teachers developed a better understanding of the importance of using MRs in physics teaching. They were also able to learn about the potential of activities that stimulate students in the search for interpretation and transposition between the different forms of representation, aiming that students appropriate the meanings of the concepts gradually according to how they understand the various representational forms (Tytler et al., 2007). From the development of activities, structured *in* and *for* the exploration of MRs, the teachers carried out a lesson that improved the learning of the subcategories of interpretation by familiarity and the inherent properties, encouraging students to interpret from a simple to a more complex representation by familiarity, or by using other inherent properties, anchored in the inherent properties of each situation, directing them to the following function of MRs (Ainsworth, 1999, 2006, 2008).

About *in-depth understandings*, it marked the stages of planning, post-lesson reflection, and development of the research lesson. The analysis showed that the teachers learned to use MRs to obtain a deeper understanding of Ohm's law. In addition, by exploring MRs, they:

(I) expanded the understanding of the data in a table, through the search for patterns of behavior of proportionality between the physical magnitudes, i.e., the relationship between the potential difference (U) and the intensity of the electric current (i);

(II) created relationships and interpretations between graphs and the respective algebraic equations of the physical magnitudes involved in Ohm's law; and

(III) generalized the algebraic expression of the electrical resistance of an Ohmic conductor.

They also learned that building graphs from data from a table facilitates qualitative understanding, interpretation, assimilation, and integration (Tytler et al., 2007). Moreover, the teachers learned to create investigative activities to promote a deeper understanding of a given content, in this case, Ohm's law. Through these activities, it was possible to go through the abstraction, extension, and relationship between the physical magnitudes involved, thus relating the various representations with the respective algebraic equations, favoring the creation of other relationships (Ainsworth, 2014). Finally, considering the complexities of MRs, teachers developed activities, analyzing what information was accessible to students and how they could use it, which encouraged them to seek an effective way to integrate several representations in the learning process (Prain et al., 2009; Wu et al., 2013).

Thus, the structure and dynamics of the research lesson on Ohm's law were constituted in a context to promote the learning of that topic (Baptista et al., 2020; Tomkelski et al., 2022) insofar as they favored the exploration of MRs and revealed their contributions to the learning of this concept, in addition to favoring new professional experiences throughout teachers' careers, contributing to their training process (Ribeiro &

Ponte, 2019; Richit & Tomkelski, 2022). It also provided moments of interaction between the teachers that made possible the confrontation and the necessary modifications to the reinterpretation of their experiences (Flores, 2004).

Thus, professional learning was related to the disciplinary field, classroom teaching, aspects of classroom teaching management, and elements of the educational context, among other processes intrinsic to teaching (Richit & Tomkelski, 2020).

CONCLUSION

Our study evidenced the teachers' professional learning about the contributions of MRs to a deeper understanding of Ohm's law. It shows that the teachers learned to use the three functions of MRs, from obtaining complementary information, passing through the constraint interpretation, and culminating in an in-depth understanding of Ohm's law. And those learnings enabled teachers to promote some changes in teaching this topic within the scope of the research lesson.

The lesson study allowed teachers to prepare a class focused on knowing and understanding the learning of Ohm's law by exploring MRs on the topic and the transition between them. And from this planning, and the concretization, observation, and reflection on the research lesson, the teachers learned about Ohm's law and how to develop this topic from MRs. When reflecting on the experience from a researcher's perspective, they realized the importance of using MRs in their professional practices.

For the teachers that participated in the lesson study, MRs mobilized by the activities developed contributed to the teaching of Ohm's law, as they could modify how to approach this concept in the classroom. The lesson study allowed them to learn about the three functions of MRs in teaching Ohm's law and, consequently, the need for interpretation and transition between the various forms of representation, which converged into a deeper understanding of the concepts.

Therefore, the investigation can contribute to discussions on the use of MRs in teaching physics topics, especially on the contributions of MRs to the deepening curriculum topics, as well as expanding the development of teachers' PCK, converging on the students' meaningful learning.

A possible limitation of this research is related to the categories of analysis and their relationship with the professional context of the participants. Because the teachers are in the same school district, we understand that professional learning in lesson study is influenced by the social, cultural, and educational aspects shared in this school district. Therefore, an analysis involving teachers from other realities may lead to different results. Besides, we understand that an analysis supported by a different theoretical framework than this could reveal others categories of MRs.

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