

Comparing students' understanding of electric and magnetic fields and forces with parallel multiple-choice questions

Eder Hernandez¹, Esmeralda Campos², Pablo Barniol³, and Genaro Zavala^{1,4,*}

¹*Tecnologico de Monterrey, Institute for the Future of Education, Monterrey 64700, Mexico*

²*University of Vienna, Austrian Educational Competence Centre Physics, Vienna 1010, Austria*

³*Tecnologico de Monterrey, School of Humanities and Education, Monterrey 64700, Mexico*

⁴*Universidad Andres Bello, Facultad de Ingenieria, Santiago 7500973, Chile*



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Understanding the parallelism between electric and magnetic phenomena can be challenging for students in introductory physics courses. This study compares students' understanding of electric and magnetic fields and forces using parallel multiple-choice questions. Most of the electricity items were drawn from our previously published Test of Understanding of Electric Field, Force, and Flux (TU-E3F), while the magnetism items were newly developed as parallel questions based on the results of our earlier studies. The participants in the present study were 232 engineering students enrolled in a calculus-based electricity and magnetism course at a private university in the northeast of Mexico. We administered a five-item electricity test and a parallel five-item magnetism test to two independent groups of 116 students each and analyzed item difficulty and response patterns using chi-square tests. In this article, we compare students' performance on parallel items and identify significant differences in the selection of the correct answers and incorrect answers. We also analyze the items by level of difficulty and identify the most frequent incorrect answers. Analysis of incorrect-answer categories highlighted recurrent difficulties with field representations, superposition, and “larger implies larger” reasoning, as well as interference between electric and magnetic ideas. Based on these results, we provide specific recommendations for improving instruction on these concepts. The analyses and recommendations can serve as valuable resources for physics education researchers and instructors teaching these topics. This study offers insights into how context influences students' conceptual understanding, with implications for enhancing electricity and magnetism education.

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I. INTRODUCTION

Several researchers have analyzed the difficulties that university students have with the concepts of electricity and magnetism [1–5]. To an expert, the relation between the electric and magnetic phenomena is based on the parallelism of Maxwell's equations and the Lorentz force equation. These phenomena may also be related to a novice, but through their parallel surface features rather than the underlying principles and meanings [6].

Several researchers have analyzed students' understanding of the concepts of electric field [7–11] and magnetic field [4,12,13]. Also, some investigators have compared the understanding of the two concepts [3–5,14–16]. Moreover, several researchers have analyzed students' understanding

of electric force [17,18] and magnetic force [19,20]. Also, a few investigators have compared the understanding of the two concepts, as in Ref. [21]. This is where we detect a need in the literature: a study that makes a global comparison of the concepts of field and force in the contexts of electricity and magnetism. This study meets this need.

In a previous work [22], we presented the design of a ten-item multiple-choice test [The Test of Understanding of Electric Field, Force, and Flux (TU-E3F)] that evaluates students' understanding of these concepts. In this article, we compare students' performance on items from this electricity test with parallel multiple-choice items on magnetism. Parallel items are those with similar surface features but different underlying principles [3–5,4,14,21]. In the context of electricity, the items in this article evaluate the concepts of electric field and electric force; in the context of magnetism, the items assess the concepts of magnetic field and magnetic force.

The research question of this study is: How do students' conceptual understanding compare across parallel multiple-choice questions on electricity and magnetism that assess the concepts of field and force? The specific objectives of

*Contact author: genaro.zavala@tec.mx

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this study are as follows: (i) To analyze students' overall performance on both parallel sets of multiple-choice questions. (ii) To compare students' performance on each of the parallel multiple-choice questions that evaluate the concepts of field and force. The significance of this study lies in its potential impact: the analyses and recommendations can serve as valuable resources for physics education researchers and instructors teaching these concepts.

II. LITERATURE REVIEW

The relevant concepts examined in this study are the electric and magnetic fields and their representations, the interactions between electric and magnetic field sources, and the interactions between electric charges and uniform electric and magnetic fields. We present this literature review using these three primary concepts as guidance, for they provide a good visualization of the findings obtained in different studies over the last two decades and the similarities they share between contexts. A recent synthesis of research on students' understandings of electricity and magnetism is provided by van Kampen and De Cock [23], which integrates many of the studies cited here and discusses recurring parallels across electrostatics and magnetostatics that motivate comparative work such as ours.

A. Electric and magnetic fields and their representations

The electric field has been considered the backbone of all electricity concepts taught in a standard course [7,8], but has proven troublesome due to its abstract nature [9–11]. Some studies show that students can use a specific representation of the electric field but cannot transform it into another representation, which has been interpreted as a lack of understanding of the electric field concept itself [4,24]. Research has also reported that, on standardized tests, this concept is usually more difficult than the mean of the other concepts [25–28].

Similar to the electric field, the magnetic field is regarded as a central concept in understanding magnetism [12]. Various studies have identified that confusion surrounding magnetic concepts stems from multiple factors, including inconsistent notations across courses and textbooks and varied interpretations of phenomena such as magnetic fields, magnetic flux, and magnetization [4,13]. One of the most common difficulties lies in the incorrect belief that magnetic fields originate from stationary electric charges, with some students even using Coulomb's law to explain magnetic interactions [29,30]. Learners tend to memorize superficial tools, such as the right-hand rule, without fully grasping the underlying principles, which often leads to misunderstandings, such as equating magnetic force with the magnetic field or neglecting the principle of superposition in magnetic contexts [4,22,30]. An additional

highlight is that students often rely on the right-hand rule rather than empirical tools like compasses when analyzing magnetic fields in classroom experiments [31].

It is not hard to see that these studies reveal several similarities, which are probably rooted in the symmetry between the two phenomena and are described by Maxwell's equations [3–5,14]. These challenges are compounded by students' limited prior exposure to field concepts. Data show that students struggle to differentiate between key concepts in electricity and magnetism, such as the electric and magnetic fields [15]. There is also research suggesting that, because most students encounter electric and magnetic fields for the first time in physics courses, their misconceptions are often shaped directly by instruction [3,16]. This could be why research shows that some difficulties may be unintended consequences of using instructional resources, such as analogies, which can potentially reinforce cognitive errors [32].

Among the most persistent misconceptions are the ideas that electric and magnetic fields behave identically in materials, that subatomic particles realign like dipoles in both cases, and that magnetic poles are simply regions of excess electric charge [33,34]. It is also common to find students thinking of magnetic poles as excessive concentrations of electric charge, which could constitute an alternative conception unintentionally perpetuated during instruction [35].

Research across both contexts suggests that the ability to switch between representations of electric and magnetic fields is closely linked to the level of conceptual understanding of the two [4,24]. Visual representations play a significant role in how students conceptualize fields. There is a well-known observation that students tend to rely on surface features, especially when field lines are involved, leading to confusion between electric and magnetic interactions [2,36]. Studies [11,24,37,38] found that students often struggle to translate field diagrams into mathematical or vector-based representations, pointing to a deeper issue in their foundational understanding. Instructional choices—such as how teachers use diagrams and metaphors—significantly affect whether students develop accurate or flawed models of electric and magnetic fields.

There is also evidence that understanding the fields is linked to the ability to apply the superposition principle [4,24] correctly. This is a key concept in introductory electromagnetism. Although some authors may consider it a mathematical tool rather than an electricity and magnetism concept [22], they still concur on most of the difficulties associated with it. It has been found that students struggle to distinguish between the field produced by an individual source and the total field at a point and often believe that only nearby sources contribute to the field [39,40]. Additionally, data suggest that students frequently misinterpret field behavior in nonsymmetric configurations, assuming uniformity where none exists [40].

Similar results can be found in Ref. [4], where students demonstrated that misunderstanding the superposition principle spans both electricity and magnetism.

B. Interactions between electric and magnetic field sources

There has been extensive research on interactions, which has identified several difficulties that even transcend different physics areas. Some works, such as Refs. [17,18], show that students often struggle to conceptually understand electric and magnetic interactions and to differentiate these forces from other physical quantities.

Research shows that a considerable number of students rely mainly on mnemonic resources when analyzing interactions between electric charges, referred to as the *rule of signs* (ROS) [21], which might be of use when working with two charges of equal magnitude, but fails in most cases where the charges are of different magnitude if it is not accompanied adequately by Coulomb's law. This is the case in studies like Ref. [41], which reported that many students misapply Newton's third law by adopting the intuitive but incorrect "Ohm's p-prim" reasoning, believing that larger charges inherently exert greater forces [42]. These preconceptions affect not only students' understanding of forces in electricity and magnetism but also their ability to apply fundamental physics principles correctly.

While electric force has been widely studied, less attention has been paid to students' conceptual grasp of magnetic interactions and the confusion that arises between the two concepts. For instance, Ref. [19] investigated students' conceptual understanding of the Lorentz force and the effectiveness of different instructional strategies. Their findings showed that students who could translate the concept of magnetic force across various forms—such as diagrams, verbal descriptions, and equations—developed a stronger conceptual grasp. These students also demonstrated superior mathematical modeling skills, aligning with observations in Ref. [20]. This makes sense, given that the Lorentz force is an abstract phenomenon that can be difficult for students to internalize due to its intangible nature [43].

Further research has examined why alternative conceptions of the Lorentz force persist. The study presented in Ref. [44] pointed to the way magnetic field sources are represented and perceived as a key influence on student understanding. The issue extends beyond students: Ref. [45] found that even some teachers struggle to describe the effects of magnetic fields generated by electric currents. Reference [32] emphasizes the need to clearly distinguish between the Lorentz force and related concepts, such as the Biot-Savart law, to help students develop a more accurate and complete understanding of magnetic fields and their associated forces.

There are still a few studies that address the similarities between the findings regarding the interaction between electric and magnetic sources as parallel phenomena.

Some findings observed while studying these two concepts simultaneously include the persistence of misconceptions originating in previous instruction, such as the impetus idea (the assumption that a moving charge must always be under the influence of a continuous force; very commonly observed in Newtonian mechanics) [3]. This tendency may reflect a broader difficulty in distinguishing force from other physical quantities, such as field [18].

C. Interactions between electric charges and uniform fields

Although research shows that students have difficulty identifying how electrically charged particles interact with electric fields [46,47], fewer studies examine the students' understanding of interactions between electric charges and uniform fields. It has been pointed out that it is really common to use this type of physical scenario for the instruction of the Lorentz force in magnetism, considering it a core example with multiple variants, but that is not the case when studying Coulomb's law, thus probably inducing students to associate these problems strictly with magnetism contexts [14]. This may be the reason why problems like this allowed the identification of the *interference* phenomenon [2]. This concept refers to students answering electricity questions using magnetism concepts, or vice versa. It has been observed mainly in problems involving interactions (between field sources and between electric charge and uniform fields). This result is consistent with previous studies [3–5,14,21,48]. The timing of instruction appeared to influence this confusion, especially when magnetism was taught closer to the time of assessment; however, previous research has shown that other factors may trigger interference, such as prior knowledge [21] or a lack of familiarity with certain concepts [14]. This pattern underscores the challenge students face in distinguishing between similar-looking phenomena governed by distinct laws.

In general, the literature contains substantial research on electric and magnetic fields and their interactions separately, but the analysis of these phenomena as parallel concepts is still ongoing. As noted in many studies [2–5,14,21,48–50], surface features have a significant impact on students' understanding and misconceptions and confusions when addressing physical problems. In addition, since electricity and magnetism naturally exhibit this parallelism, it is only to be expected that such confusions arise when analyzing them simultaneously and through a variety of strategies. We have identified and addressed the need for a parallel study on electricity and magnetism through qualitative studies, using phenomenography [3–5,14,48,51]. Now, with the present study, we aim to strengthen this research using quantitative methods that allow us to make a more detailed comparison of students' understanding of the concepts of field and force in the contexts of electricity and magnetism. Recognizing the

presence of these alternative conceptions and their root causes is a critical step toward improving conceptual understanding in physics.

III. METHODOLOGY

This study employed a quantitative, cross-sectional design [52]. The instrument, participants, and data collection procedures are detailed below.

A. Instrument

The instrument for this study included ten parallel multiple-choice items: five on electricity and five on magnetism. All items are presented in Appendix A (electricity) and Appendix B (magnetism). We referred to the electricity questions as set E; thus, we labeled the items E1, E2, E3, E4, and E5, as described in Table I. The five items in set E included four items from the TU-E3F (E2-E5) [22] and one

item (E1) adapted to a multiple-choice format from our previous study on electric interactions [21]. Item E1 was created using the same strategy as those presented in the TU-E3F: first, we identified the most common categories that emerged from a phenomenographic analysis, and then we created possible answers to this question. We included item E1 in this study, even though it was not included in the TU-E3F, because it allows us to observe the tools students use to represent an electric field and the difficulties they may encounter while doing so. As will be described further below, this question might have two options that show conceptual understanding of the electric field, but only one is correct, given the way the question is asked.

The TU-E3F items used in this study correspond to the same version whose psychometric properties were previously reported for a similar population of engineering students [22]. For the present study, we used the same wording as in that validated version.

TABLE I. Description of the items used in this study.

Concept	Topic	Pair of items	Description of the items	Sources of our previous studies
Field	Field as a vectorial quantity	1	E1. <i>A point charge (+q) is presented. It asks to choose the representation of the electric field in two positions equidistant from the charge.</i>	[4]
			M1. <i>A wire that conducts a conventional electric current (I_0) in the direction out of the sheet is presented. It asks to choose the representation of the magnetic field in two positions equidistant from the wire.</i>	[4]
	Field superposition principle	2	E2. <i>Two fixed-point charges (+q and -q) are presented. It asks to choose the representation of the electric field in a position.</i>	TU-E3F [22]
			M2. <i>Two fixed wires that conduct conventional currents (I_0) in opposite directions, one outward and one inward of the sheet, are presented. It asks to choose the representation of the magnetic field in a position.</i>	[4]
Force	Forces between sources	3	E3. <i>Two fixed-point charges (+q and +3q) are presented. The question asks to choose the representation of the force exerted on each charge.</i>	TU-E3F [22]
			M3. <i>Two fixed wires that conduct conventional electric currents in the direction out of the sheet (I_0 and $3I_0$) are presented. It asks to choose the representation of the force exerted on each wire.</i>	[21]
	Force exerted on a charge at rest within a field	4	E4. <i>A point charge +q, at rest, within an electric field is presented. It asks to choose the representation of the direction of the force on the charge.</i>	TU-E3F [22]
			M4. <i>A point charge +q, at rest, within a magnetic field is presented. It asks to choose the representation of the direction of the force on the charge.</i>	[3]
	Force exerted on a charge in motion within a field	5	E5. <i>A point charge +q, in motion, within an electric field is presented. It asks to choose the representation of the direction of the force on the charge.</i>	TU-E3F [22]
			M5. <i>A point charge +q, in motion, within a magnetic field is presented. It asks to choose the representation of the direction of the force on the charge.</i>	[3]

We referred to the magnetism questions as set M; thus, we labeled the items M1, M2, M3, M4, and M5, as presented in Table I. These five magnetism problems were designed to be parallel to the E set, and the included options were derived from previous studies we conducted [3,4,21]. The options for these questions were created based on the results reported in the studies, while considering the descriptive categories that appeared in the set E questions, so that they would remain as parallel as possible and allow for comparison. This means that some descriptive categories that emerged in the analysis of the open-ended version of these problems may not have made it to the final closed questions if they did not have a parallel version in set E. All items on electricity and magnetism were presented in Spanish.

B. Data collection

The participants were 232 engineering students enrolled in a calculus-based electricity and magnetism course at a private university in the northeast of Mexico. These students were all part of one of the university's undergraduate engineering programs, which required them to study three introductory physics courses: the first focused on classical mechanics, the second on fluid mechanics and thermodynamics, and the third on electricity and magnetism. The participants were informed of the study's objective and that their participation would not affect their grades. Participation was anonymous and voluntary. We administered sets E and M to 116 students each. The different sets were distributed randomly to all students to ensure homogeneity of the sample. Although each form was administered to 116 students, this sample size is appropriate for the item-level indices reported here (difficulty, discrimination, and point-biserial) and for the chi-square comparisons of response distributions, because expected counts per option remain above common minimum thresholds. Nevertheless, the modest N per form reduces sensitivity to small differences between contexts; therefore, nonsignificant comparisons should be interpreted as an absence of evidence of a difference at this sample size rather than evidence of equivalence.

C. Data analysis

In the first step of this analysis, we evaluated the reliability and discriminatory power of the items used in this study. To make this analysis, we performed the three

statistical tests suggested by Ding *et al.* in Ref. [25] that focus on individual test items: (i) the item difficulty index, (ii) the item discrimination index, and (iii) the item point-biserial coefficient. The second step focuses on analyzing students' performance on both sets of questions (objective 1). This step concentrates on analyzing average scores across the two tests and grouping items by difficulty level.

Then we compared students' performance on each pair of items (objective 2). To make this comparison, we first grouped multiple incorrect responses into categories. To compare students' performances and detect significant differences in each pair of items, we used the chi-square test following the procedure described in Ref. [53]. First, we used the chi-square test ($p < 0.05$) to determine whether there was a significant difference in the distribution of categories between the two items. If there was, we then determined which specific category was significantly different using the chi-square test. To avoid inflating the type I error rate, we used the Bonferroni correction, dividing the original p value (0.05) by the total number of comparisons (5, one for each multiple-choice option) to obtain a conservative p value of 0.01. Finally, we performed a global analysis of the trends across all items and, for instructional purposes, identified the incorrect categories with a frequency rate greater than 20%.

IV. ANALYSIS OF THE ITEMS

Table II presents the analysis of the difficulty index (P), the discriminatory power (D), and the point-biserial coefficient (r_{pbs}) for the 10 items used in this study. Most items' P values are within an acceptable range of 0.2-0.8 [54,55], except for E3 and M3. The average P of the E set is 0.33 and that of the M set is 0.32. All items' D and r_{pbs} are above the acceptable 0.2 threshold [25,55,56]. The average D for the E set is 0.70, and for the M set is 0.71. The average r_{pbs} for the E set is 0.59, and for the M set is 0.62.

V. STUDENTS' OVERALL PERFORMANCE ON BOTH PARALLEL SETS OF MULTIPLE-CHOICE QUESTIONS

In this section, we cover objective 1 of this study: To analyze students' overall performance on both parallel sets of multiple-choice questions. We present an analysis of students' overall performance on both tests. The average

TABLE II. Difficulty index (P), discriminatory index (D), and point-biserial coefficient (r_{pbs}) for the items used in this study.

	Electricity items						Magnetism items					
	E1	E2	E3	E4	E5	Average	M1	M2	M3	M4	M5	Average
P	0.41	0.43	0.18	0.41	0.22	0.33	0.34	0.34	0.08	0.34	0.53	0.32
D	0.62	0.90	0.45	0.90	0.66	0.70	0.79	0.90	0.21	0.79	0.86	0.71
r_{pbs}	0.55	0.65	0.48	0.68	0.61	0.59	0.67	0.73	0.44	0.66	0.61	0.62

TABLE III. Percentages of students selecting a particular choice for each item. The correct answer is in boldface, and N is for students who did not answer.

Concept	Topic	Pair of items	Item	A (%)	B (%)	C (%)	D (%)	E (%)	F (%)	G (%)	H (%)	N (%)
Field	Field as a vectorial quantity	1	E1	4	8	10	41	18	19			0
			M1	4	54	6	1	1	34			0
	Field superposition principle	2	E2	11	1	7	21	43	16			1
			M2	3	35	39	3	3	17			0
Force	Forces between sources	3	E3	18	22	52	3	4	0	0	1	0
			M3	4	17	18	8	16	16	9	11	1
	Force exerted on a charge at rest within a field	4	E4	41	13	11	7	9	3	15		1
			M4	11	8	13	12	17	4	34		1
	Force exerted on a charge in motion within a field	5	E5	10	30	4	3	22	5	24	1	1
			M5	8	53	1	5	7	3	22	1	0

test score in electricity was 1.66 out of 5, and the average test score in magnetism was 1.62 out of 5, with each item worth 1 point. This means that students with average scores on both tests struggled to answer three of the five test items correctly. Expressed as percentages, these correspond to 33% and 32%, respectively, and align with the average difficulty index values of 0.33 and 0.32 (Table II). The score distribution is positively skewed, indicating that most students scored at the lower end of the scale, suggesting that the test was challenging for them.

Table III shows the percentages of students who selected each option for each item in both tests. As shown in this table, the percentages of correct answers across the two tests are generally low, ranging from 8% in item M3 to 53% in item M5. Following the analyses of previous studies [22,28,57], we categorized the test items of both tests based on their difficulty levels. Items were classified as “high” difficulty if 30% or fewer students answered correctly, “medium” difficulty if the proportion of correct answers ranged from 30% to 60%, and “low” difficulty if 60% or more students answered correctly. Table IV shows the division of items by difficulty level.

An interesting result in Table IV is that four of the five pairs of items are at the same difficulty level. Only pair 5, which evaluates students’ understanding of the force exerted on a charge in motion within a field, is at two different levels of difficulty: item E5 is at the high difficulty level with a correct response percentage of 22%, while item M5 is at the low difficulty level with a correct response percentage of 53%. This difference will be developed in Secs. VI and VII.

Another important result in the table is that three items are at the high level of difficulty. The pair of items 3 evaluates students’ understanding of forces between sources. As mentioned above, item E5 assesses students’ understanding of the force exerted on a charged particle in motion in an electric field. Finally, the table shows that items 1, 2, and 4 are at the medium level of difficulty.

VI. COMPARISON OF STUDENTS’ PERFORMANCE ON EACH OF THE PARALLEL ITEMS

In the following two sections, we cover objective 2 of this study: to compare students’ performance on parallel multiple-choice items in electricity and magnetism that evaluate the concepts of field and force. In the following subsections, we compare students’ understanding of the pairs of related items separately.

A. Field as a vectorial quantity: Items E1 and M1

In this analysis, it is worth noting that E1 and M1 are nonstandard multiple-choice items, with some options that students could consider correct. In E1, option E shows an electric field line diagram, and option F presents two lines that start at the charge and end at the two positions P and S , respectively (a hybrid representation of vectors and field lines). In M1, option B shows a magnetic field line corresponding to the current’s magnetic field. Representationally, using vector arrows is the most direct way to specify the field at particular locations because they explicitly encode the field vector (direction and relative magnitude) at a point, whereas field-line diagrams are primarily intended to

TABLE IV. Division of items by difficulty level.

Item difficulty level	Range of correct answer percentages	Items
High	$\leq 30\%$	Pair of items 3 (E3-M3); E5
Medium	(30%, 50%)	Pair of items 1, 2, 4 (E1-M1; E2-M2; E4-M4)
Low	$\geq 50\%$	M5

TABLE V. Comparison between contexts for questions E1 and M1. A mark ($\leftrightarrow$) has been placed in those categories in which a significant difference has been obtained between contexts.

Category	E1		Significant difference	M1	
	Category option (% per option)	Category total (%)		Category option (% per option)	Category total (%)
Physics principles (correct)	Option D (41%)	41		Option F (34%)	34
Alternative representations	Option E (18%) and Option F (19%)	37	$\leftrightarrow$	Option B (54%) and Option D (1%)	55
Interference	Option B (8%) and Option C (10%)	18	$\leftrightarrow$	Option A (4%) and Option E (1%)	5
Opposite direction	Option A (4%)	4		Option C (6%)	6

convey the global spatial structure of the field across a region (with direction inferred from the local tangent and relative strength from line density) [58]. Moreover, it has been shown that hybrid representations of vectors and field lines can create difficulties for students [4,11,24]. As the question specifically asked for the best way to represent the field at each position P and S , options E and F in E1 and option B in M1 are alternative representations, not correct answers.

As mentioned before, we grouped multiple-choice options into meaningful categories to allow for comparison. In this pair of items 1, there are three categories of incorrect answers: (i) “Alternative representations”: students choose options that include hybrid representations of vectors and field lines, or field-line diagrams, (ii) “Interference”: students choose answers with parallel context elements, and (iii) “Opposite direction”: students choose an answer with this characteristic. Table V shows the response selection percentages for each option and each category for items E1 and M1. Using the chi-square test, in these items, we found that there are significant differences between contexts at least in one category [$\chi^2(3, N = 232) = 13.5323$, $p = 0.003616$]. In Table V, a mark ($\leftrightarrow$) is placed in those categories in which a significant difference between contexts has been obtained. In these items, no significant differences were observed in the selection of the correct answer [$\chi^2(1, N = 232) = 1.1825$, $p = 0.276839$].

We detected significant differences in the selection of two incorrect categories. The first category is “Alternative representations” [$\chi^2(1, N = 232) = 7.6495$, $p = 0.005679$], with higher selection in the context of magnetism (55% vs 37%). This indicates that response options consistent with this category are more attractive distractors for students in the context of magnetism than in that of electricity. The second category is “Interference” [$\chi^2(1, N = 232) = 9.4309$, $p = 0.002134$], with higher selection in the context of electricity (18% vs 5%). This result confirms that students are more likely to experience interference from concepts of magnetism when answering questions about the electric field than vice versa. Finally, no significant differences were found in the selection of the “Opposite direction” category.

B. Field superposition principle: Items E2 and M2

Table VI exhibits the response selection percentages for each option and each category for items E2 and M2. In this pair of items 2, there are four categories of incorrect answers: (i) “Contribution from each source”: students choose an answer with the contribution of the field made by each source but do not perform the addition, (ii) “Interference”: students choose answers with parallel context elements, (iii) “Difficulties in graphical vector addition”: students choose answers with resulting vectors in a different direction, applying the superposition principle with difficulties, and (iv) “Vectors cancel”: students choose an answer with this characteristic. Using the chi-square test, in these items, we also observed that there are significant differences between contexts at least in one category [$\chi^2(4, N = 230) = 11.3142$, $p = 0.023251$]. In these items, no significant differences were found in the selection of the correct answer [$\chi^2(1, N = 230) = 2.1225$, $p = 0.145154$].

In these items, we detected a significant difference in the selection of an incorrect category: “Contribution from each source” [$\chi^2(1, N = 230) = 8.6168$, $p = 0.003331$], with higher selection in the context of magnetism (39% vs 21%). This result suggests that drawings presenting the field contribution of each individual source are more attractive to students in a magnetism context than in an electricity context. Likewise, the result implies that students may be clear about the contribution of each source (part of the superposition principle) but not about the vector representation of the fields, as they are aware that each source must be considered but do not produce the expected vector result. Finally, no significant differences were found in the selection of the other categories.

C. Forces between sources: Items E3 and M3

Table VII presents the response selection percentages for each option and each category for items E3 and M3. In this pair of items 3, there are also four categories of incorrect answers: (i) “larger implies larger (Ohm’s p-prim)”: students choose an answer that shows a greater force exerted by the larger source on the smaller source, (ii) “Inverse

TABLE VI. Comparison between contexts for questions E2 and M2. A mark ($\leftrightarrow$) has been placed in those categories in which a significant difference has been obtained between contexts.

Category	E2		Significant difference	M2	
	Category option (% per option)	Category total (%)		Category option (% per option)	Category total (%)
Physics principles (correct)	Option E (43%)	43	$\leftrightarrow$	Option B (35%)	35
Contribution from each source	Option D (21%)	21		Option C (39%)	39
Interference	Option A (11%)	11		Option D (3%) and Option E (3%)	6
Difficulties in graphical vector addition	Option B (1%) and Option C (7%)	8		Option A (3%)	3
Vectors cancel	Option F (16%)	16		Option F (17%)	17

Ohm's p-prim": students choose an answer that shows a greater force exerted on the larger source by the smaller source, (iii) "Interference": students choose answers that included elements of the parallel context, and (iv) "There is no force": students choose an answer that explicitly mentioned that the force was zero. It is worth noting that option G in the magnetism test is not included in the table, as it represents the category "Force-Field confusion," which cannot be identified in the electricity item. Although it could be present in the electricity test, a student presenting this difficulty would select any answer among options A, B, or C, as they are, making it impossible to identify the reasoning that led them to their selection.

Using the chi-square test, in these items, we also observed that there are significant differences between contexts at least in one category [$\chi^2(5, N = 220) = 62.6199$, $p < 1.00 \times 10^{-5}$]. Additionally, in these items, no significant differences were found in the selection of the correct answer [$\chi^2(1, N = 220) = 4.3755$, $p = 0.036458$].

Significant differences were found in these items in the selection of three incorrect categories. The first category is "larger implies larger (Ohm's p-prim)" [$\chi^2(1, N = 220) = 27.6968$, $p < 1.00 \times 10^{-5}$], with higher selection in the

context of electricity (52% vs 16%). This result suggests that students are more likely to rely on the "larger implies larger" intuition (often discussed as diSessa's Ohm's p-prim) [42] in the electricity context than in the magnetism context, given the circumstances and other available options. More specifically, this response pattern can also be interpreted as difficulty applying Newton's third law (equal and opposite interaction forces) to noncontact interactions, a tendency closely related to the broader "large implies large" spontaneous reasoning documented in mechanics and known to shape reasoning across contexts [59]. Prior work also shows that students' mechanics background can influence how they conceptualize interactions in electromagnetism [60]. The second category is "Interference" [$\chi^2(1, N = 220) = 32.0104$, $p < 1.00 \times 10^{-5}$], with higher selection in the context of magnetism (39% vs 7%). This suggests that students are more likely to attempt to analyze the interaction between two electric currents as if they were electric charges, possibly because the latter phenomenon is more familiar to them, specifically the ROS, as described in Ref. [21]. The third category is "There is no force" [$\chi^2(1, N = 220) = 11.0063$, $p = 9.08 \times 10^{-4}$], with also higher selection in the context of magnetism (10% vs 1%). This indicates that it is

TABLE VII. Comparison between contexts for questions E3 and M3. A mark ($\leftrightarrow$) has been placed in those categories in which a significant difference has been obtained between contexts.

Category	E3		Significant difference	M3	
	Category option (% per option)	Category total (%)		Category option (% per option)	Category total (%)
Physics principles (correct)	Option A (18%)	18	$\leftrightarrow$	Option D (8%)	8
Larger implies larger (Ohm's p-prim)	Option C (52%)	52		Option F (16%)	16
Inverse Ohm's p-prim	Option B (22%)	22	$\leftrightarrow$	Option E (16%)	16
Interference	Option D (3%); Option E (4%); Option F (0%); Option G (0%)	7		Option A (4%); Option B (17%); Option C (18%)	39
There is no force	Option H (1%)	1	$\leftrightarrow$	Option H (11%)	11

TABLE VIII. Comparison between contexts for questions E4 and M4. A mark ($\leftrightarrow$) has been placed in those categories in which a significant difference has been obtained between contexts.

Category	E4		Significant difference	M4	
	Category option (% per option)	Category total (%)		Category option (% per option)	Category total (%)
Physics principles (correct)	Option A (41%)	41		Option G (34%)	34
Interference	Option C (11%); Option D (7%); Option E (9%); Option F (3%); Option G (15%)	45	$\leftrightarrow$	Option A (11%) Option B (8%)	19
Incorrect use of laws (Coulomb or Lorentz)	Option B (13%)	13	$\leftrightarrow$	Option C (13%); Option D (12%); Option E (17%); Option F (4%)	46

more likely to encounter this conceptual difficulty in the case of magnetism. Likely, this result is strongly related to those obtained for the pair of questions on interactions of electric charges with fields, shown in the following subsections. Last of all, no significant differences were found in the selection of the other categories.

D. Force exerted on a charge at rest within a field: Items E4 and M4

Table VIII shows the response selection percentages for each option and each category for items E4 and M4. In this pair of items 4, there are two categories of incorrect answers: (i) “Interference”: students choose answers with parallel context elements, and (ii) “Incorrect use of laws”: students choose answers that involve inappropriate use of Coulomb’s Law (in the context of electricity) or Lorentz’s Law (in the context of magnetism). Using the Chi square test, in these items we observed that there are significant differences between contexts at least in one category [$\chi^2(2, N = 230) = 35.1367, p < 1.00 \times 10^{-5}$]. Furthermore, in these items, no significant differences were detected in the selection of the correct answer [$\chi^2(1, N = 230) = 1.4975, p = 0.221061$].

Significant differences were found in the selection of both incorrect categories. The first category is “Interference” [$\chi^2(1, N = 230) = 17.9314, p = 2.30 \times 10^{-5}$], with higher selection in the context of electricity (45% vs 11%). This result suggests that students are more likely to analyze the system of an electric charge at rest within an electric field using magnetism resources than vice versa. The second category is “Incorrect use of laws” [$\chi^2(1, N = 230) = 31.4907, p < 1.00 \times 10^{-5}$], with higher selection in the context of magnetism (46% vs 13%). This category includes answers that involved a mistaken use of Coulomb’s law or Lorentz’s law. This difference is possibly attributable to the lack of a deep understanding of Lorentz’s law, since it was in magnetism where this set of distractors had the most impact.

E. Force exerted on a charge in motion within a field: Items E5 and M5

Table IX presents the response selection percentages for each option and each category for items E5 and M5. In this pair of items 5, there are four categories of incorrect answers: (i) “Interference”: students choose answers with

TABLE IX. Comparison between contexts for questions E5 and M5. A mark ($\leftrightarrow$) has been placed in those categories in which a significant difference has been obtained between contexts.

Category	E5		Significant difference	M5	
	Category option (% per option)	Category total (%)		Category option (% per option)	Category total (%)
Physics principles (correct)	Option E (22%)	22	$\leftrightarrow$	Option B (53%)	53
Interference	Option A (10%); Option B (30%); Option C (4%); Option D (3%)	47	$\leftrightarrow$	Option E (7%) Option F (3%)	10
There is no force	Option H (1%)	1		Option H (1%)	1
Vector sum of velocity and field	Option G (24%)	24		Option G (22%)	22
Incorrect use of laws (Coulomb or Lorentz)	Option F (5%)	5		Option A (8%); Option C (1%); Option D (5%)	14

parallel context elements, (ii) “There is no force”: students choose an answer with this characteristic, (iii) “Vector sum of velocity and field”: students choose an answer of a vector between velocity of the charge and the field (misconception of the pre-Galilean “force” needed to keep objects in motion [17]), and (iv) “Incorrect use of laws”: students choose answers that involve inappropriate use of Coulomb’s law (in the context of electricity) or Lorentz’s law (in the context of magnetism).

Using the chi-square test, in these items, we also observed that there are significant differences between contexts at least in one category [$\chi^2(4, N=232) = 49.1778$, $p < 1.0 \times 10^{-5}$]. Unlike all the previous items, significant differences were found in the selection of the correct answer [$\chi^2(1, N=232) = 22.5287$, $p < 1.0 \times 10^{-5}$], with higher selection in the context of magnetism (53% vs 22%). This result shows that students have less difficulty answering this item correctly in the context of magnetism and supports the initial finding of this concept being of different complexity depending on the context, as pointed out in Sec. V. Since this is the only case among the five pairs of items where the correct answer shows a significant difference, we will dwell on this result in Sec. VII.

In these items, we detected a significant difference in the selection of an incorrect category: “Interference” [$\chi^2(1, N=232) = 40.996$, $p < 1.00 \times 10^{-5}$], with higher selection in the context of electricity (47% vs 7%). This result suggests that students are more likely to analyze the system of electric charge moving within an electric field using magnetism resources than vice versa. Finally, no significant differences were found in the selection of the other categories.

VII. OVERALL COMPARISON OF STUDENT PERFORMANCE ON PARALLEL ITEMS

In this section, following objective 2, we conduct a global analysis of the trends detected in all items. Table X presents information on the significant differences observed across the five pairs of items.

A. Significant differences in the selection of the correct answer

As the first important finding of this comparison overview, it is interesting to note that there is only one significant difference in the selection of the correct answer

TABLE X. Information related to the significant differences found in the five pairs of items.

Items and subtopic	Correct answer selection (%)	Incorrect categories with significant differences in selection	Incorrect categories with no significant differences in selection
E1-M1. Field as a vectorial quantity	No significant difference (E:41%; M: 34%)	-Interference (higher selection in electricity, E:18%; M:5%) -Alternative representations (higher selection in magnetism, E:37%; M:55%)	-Opposite direction
E2-M2. Field superposition principle	No significant difference (E:43%; M:34%)	-Contribution from each source (higher selection in magnetism, E:21%; M:39%)	-Interference -Difficulties in graphical vector addition -Vectors cancel
E3-M3. Forces between sources	No significant difference (E:18%; M:8%)	-Larger implies larger (Ohm’s p-prim) (higher selection in electricity, E:52%; M:16%) -Interference (higher selection in magnetism, E:7%; M:39%). -There is no force (higher selection in magnetism, E:1%; M:10%)	-Inverse p-prim
E4-M4. Force exerted on a charge at rest within a field	No significant difference (E:41%; M:34%)	-Interference (higher selection in electricity, E:45%; M:11%) -Incorrect use of laws (Coulomb or Lorentz) (higher selection in magnetism, E:13%; M:46%)	No category
E5-M5. Force exerted on a charge in motion within a field	Significant difference. Higher selection in magnetism (E:22%; M:53%)	-Interference (higher selection in electricity, E:47%; M:7%)	-There is no force -Vector sum of velocity and field -Incorrect use of laws (Coulomb or Lorentz)

in one pair of items (item 5) that evaluates students' understanding of the force exerted on a charge with velocity v (i.e., a moving charge) within a uniform field. As observed in a previous section (Table IV), item pair 5 was the only pair in which the items differed in difficulty. The item in the context of electricity (E5) was at a high difficulty level (22% correct response), and the item in the context of magnetism (M5) was at a low difficulty level (53% correct response). As can be seen, the percentage of correct responses in magnetism is much higher than in electricity.

A possible explanation for this result could be the "familiarity" of the scenario in item pair 5. Usually, item M5 is a typical problem in teaching magnetism and is used repeatedly during instruction, whereas item E5 is less common in teaching electricity concepts. M5 is a relatively common type of problem in the teaching of Lorentz's law in magnetism and also involves more complex elements, such as the right-hand rule, which demand a deeper analysis and favor memorization [2]. Moreover, as in other scenarios, this is a relatively common problem during instruction, as reported in the textbook [61] and the tutorials [62] used for this course with our population.

Also, as discussed in the following subsection, this is the pair of items with the most significant selection difference in the "Interference" category (notably higher in electricity). In other words, more students are answering the electricity question as if it were a magnetism question than vice versa, probably because the problem presents surface features, supporting the idea that students are more familiar with this type of problem in the magnetism context.

B. Significant differences in the selection of the distractors related to interference

It is interesting to note in Table X that four of the five item pairs show significant differences between contexts in the selection of the incorrect category of "Interference." The only pair of items for which this is not observed is pair 2, which evaluates the principle of superposition of fields. The fact that this pair of items is the only one in which it does not appear may be because this item is the only one that focuses on evaluating a procedure.

For the first pair of items, E1 and M1, which assess the conceptual understanding of the field as a vector quantity, it is observed that it is more common to represent an electric field as a magnetic field than vice versa. This could be due to the timing of the test administration, which is much closer to the teaching of magnetism than to that of electricity. This is probably the result of the instruction and resources the teacher uses to represent the field in different contexts, as has been suggested in previous studies [2,14,32,44,63].

For the third pair of items, E3 and M3, which address understanding the forces between two sources, it was found

that it is more common to treat the interaction between two electric currents as if they were electric charges than vice versa. The familiarity of the scenario is proposed as a probable cause for this finding. As explained before, the direct interaction between two field sources is addressed much more frequently during the teaching of Coulomb's law. It is also likely that the law of signs' memorization resource is added as a factor to consider in this phenomenon. Being typical and, in general, useful in the analysis of interactions between electric charges, it becomes a tool for interactions between electric currents, thereby producing interference. This finding is consistent with that reported in Ref. [21].

A similar idea could be said of the pairs of items E4 and M4 and E5 and M5, which assess understanding of the interaction between a static electric charge (E4 and M4) and a uniform field, or a charge in motion (E5 and M5) and a uniform field. The results, like those of Refs. [2,3], indicate that it is more common to analyze the interaction between electric charges and uniform electric fields using magnetism resources than vice versa. The possible cause is also associated with the familiarity of the scenario. Analyzing an electric charge in a uniform field and its interaction is a very common type of problem in the teaching of Lorentz's law in magnetism, and it also involves more complex elements, such as the right-hand rule, which demand a deeper analysis and favor memorization. This then causes students to try to use these tools even in electricity problems, leading to interference as they are carried away by the superficial characteristics of the diagrams presented for each scenario [50,64].

C. Significant differences in the selection of other distractors

Finally, Table X also shows that in four of the five item pairs, there is at least one significant difference in the selection of a distractor other than the "interference" error. In item pair 3, two distractors are observed with a significant difference in their selection, and in item pairs 1, 2, and 4, only one distractor is observed with a significant difference in its selection. We analyze these differences below.

In the first pair of items (E1 and M1), which assess the understanding of the field as a vector quantity, it is observed that there is a significant difference in the category of "Alternative representations," with this being more common in magnetism (E:37%; M:55%). The instruction could cause this representation problem, since it is common to represent the magnetic field with circular field lines around the source, while neglecting its vectorial representation using vector arrows. On the other hand, in electric field problems, it is very common to use vector arrows to represent the field at a given point.

This finding, furthermore, could be related to that of the second pair of items (E2 and M2), which assesses the

understanding of the principle of superposition of fields. Technically, this concept is not specific to electromagnetism but could be viewed as a vector algebra question (specifically, a sum of vectors). This is why the “Contribution from each source” category shows a higher frequency in magnetism (E:21%; M:39%), as students might not be identifying the magnetic field as a vectorial quantity, which then prevents them from performing vector addition to find the resulting magnetic field.

In the case of the third pair of items (E3 and M3) that assess the understanding of interactions between field sources, two descriptive categories stand out with significant differences between contexts: “larger implies larger (Ohm’s p-prim)” (higher selection in electricity, E:52%; M:16%) and “There is no force” (higher selection in magnetism, E:1%; M:10%). Responses related to the “larger implies larger (Ohm’s p-prim)” category are more common in electricity than in magnetism, and two possible causes are proposed for this result. The first is that the analysis of interactions between two electric charges is relatively more common in electricity instruction, serving as the classic example of Coulomb’s law in the textbook [61] and the tutorial manual for the lab sessions used during the course [62]. However, Lorentz’s law is usually taught with a broader range of examples, following the same teaching path observed in those same resources. The interaction between two electric currents is limited to these examples and is not as common as the interaction between electric charges and uniform fields. This adds to the fact that the force between two electric currents requires a deeper analysis, involving mathematical concepts of greater complexity, possibly requiring conscious analysis of the phenomenon. The second cause, not necessarily independent of the first, is that the interaction of electric charges is more direct and related to mechanical interactions (where the p-prim model is very common). In addition, the same distractor pattern is consistent with students treating the interaction asymmetrically (i.e., assigning different force magnitudes to the two sources), which reflects difficulty coordinating electromagnetism with Newton’s third law reasoning about interaction pairs; this kind of cross-domain influence from mechanics to electromagnetism is documented in the literature [58,59]. In any case, the students’ focus in this category is on the fact that one of the two sources is of greater magnitude than the other, a superficial characteristic immediately noticeable when facing the problem. These results coincide with those reported in Refs. [1,21,63].

For the “There is no force” category, the opposite occurs: the significant differences indicate that this difficulty is more frequently found in magnetism (E:1%; M:10%). Although some ideas emerged to explain this, such as the possibility that students might confuse one of the electric currents with charges due to the representation (which would represent an interference-like difficulty), we

consider percentages are too low for a thorough analysis. In short, more research is needed to support this or any other claim that explains this result, so we leave it open for further studies.

Finally, in the fourth pair of items (E4 and M4), which assess the understanding of the force exerted on a charge at rest within a field, it is observed that there is a significant difference in the category of “Incorrect use of laws (Coulomb or Lorentz),” this being more common in magnetism (E:13%; M:46%). The proposed cause of this result lies in the superficial characteristics of the laws. Coulomb’s law states that the electric force is parallel to the field that produces it, giving only a couple of possible direction options, which are also independent of the movement of the electric charge. On the other hand, Lorentz’s law states that the force due to the magnetic field is perpendicular to the magnetic field, giving four possible directions in the options, and the speed of the charged particle must also be considered. It is likely that students, perhaps by rote memorization, are focusing only on the direction of the field in their answer, and, as there is more opportunity for error in the context of magnetism (because there are more answers that match the description), these types of errors occur in this context more frequently. The idea of using memory resources has been raised in research such as [2,3,5,14], but results of this type have not been observed so frequently.

VIII. IDENTIFICATION OF INCORRECT CATEGORIES WITH HIGHER FREQUENCY PERCENTAGES

For instructional purposes, we identify the incorrect categories with a frequency rate greater than 20%. Table XI shows the nine incorrect categories that fulfill this criterion.

When analyzing Table XI, three interesting patterns are observed. The first pattern is that, among the nine most frequent categories, three appear in both contexts with percentages greater than 20%. These three categories are: (i) “Alternative representations” (in item pair 1), (ii) “Contribution from each source in both contexts” (in item pair 2), and “Vector sum of velocity and field” (in item pair 5).

The second pattern is that the other three categories are from the “Interference” category. Two of these categories are in the context of electricity (pair of items 4 and 5, that is, E4 and E5, which are the items that evaluate the understanding of the force on a charge in an electric field, whether at rest or in motion), and one category is in the context of magnetism (item pair 3, that is, M3, which evaluates the understanding of the interaction forces of two currents).

Finally, the three remaining categories are of other distractors: (i) and (ii) “larger implies larger (Ohm’s p-prim)” and “Inverse Ohm’s p-prim,” in the third pair of items, that is, E3, which evaluates the understanding of

TABLE XI. Incorrect categories with frequency rates greater than 20%.

Items and subtopics	Incorrect categories (%)
E1-M1. Field as a vectorial quantity	1. "Alternative representations" in both contexts (E:37%; M:55%)
E2-M2. Field superposition principle	2. "Contribution from each source" in both contexts (E:21%; M:39%)
E3-M3. Forces between sources	3. "Larger implies larger (Ohm's p-prim)" in electricity (52%)
	4. "Inverse Ohm's p-prim" in electricity (22%)
	5. "Interference" in magnetism (39%)
E4-M4. Force exerted on a charge at rest within a field	6. "Interference" in electricity (45%)
	7. "Incorrect use of laws (Lorentz law)" in magnetism (46%)
E5-M5. Force exerted on a charge in motion within a field	8. "Interference" in electricity (47%)
	9. "Vector sum of velocity and field" in both contexts (E:24%; M:21%)

the forces between two charges, and (iii) incorrect use of Lorentz's law in item pair 4, which evaluates the understanding of the force on a charge at rest within a magnetic field.

IX. CONCLUSIONS

The research question of this study is: How do students' conceptual understanding compare across parallel multiple-choice questions on electricity and magnetism that assess the concepts of field and force? The first specific objective of this study was to analyze students' overall performance on both parallel sets of multiple-choice questions. To this end, we analyzed students' overall performance on both tests. We found that both tests were difficult for the students, and that students scoring average scores in both tests had trouble answering three of the five test items correctly. We also found that three of the ten items across both tests were at a high level of difficulty with correct answer percentages lower than 30%: two items were from item 3 pair, which evaluates students' understanding of forces between sources, and one item was item E5, which evaluates students' understanding of the force exerted on a charge in motion within an electric field. Another interesting result is that the parallel item of the latter, item M5, which evaluates this understanding in the context of magnetism, was, in contrast, at a low difficulty level, with a correct answer percentage above 50%. We discuss this difference in line with objective 2 of this study.

Another significant result in the table is that three items are at the high level of difficulty. Item pair 3 evaluates students' understanding of forces between sources. As mentioned above, item E5 evaluates students' understanding of the force exerted on a charge in motion within an electric field. Finally, it is observed from the table that pairs of items 1, 2, and 4 are at the medium level of difficulty.

The second specific objective of this study was to compare students' performance on each of the parallel multiple-choice questions that evaluate the concepts of field and force. We identified that students' correct responses generally did not vary significantly across contexts (electricity vs magnetism), except for one specific understanding: the interaction of a moving charge with a uniform field.

Better performance in magnetism was observed in this case, which could be due to our students' greater familiarity with the specific scenarios typically emphasized in this context. This pattern aligns with findings from previous qualitative phases and related research [2,3].

Another important outcome is that students exhibited greater conceptual difficulties in magnetism across most understandings. Key recurring issues included confusion related to hybrid vectors and source contributions when reasoning about fields, as well as interference when analyzing interactions between field sources. These difficulties were much more common in magnetism and reflected trends reported in previous studies [4,9]. The results support the notion that magnetism, being less familiar to students than electricity, leads to a greater reliance on surface features [43,50].

However, some difficulties were more prevalent in the electricity context. For example, interference-related misconceptions were more frequent in electricity for questions related to interactions between electric charges and uniform fields, consistent with studies in Refs. [1,2]. The suggested explanations include students' reliance on surface features, the timing of the assessment relative to instruction, and the impact of prior experience with similar problems. This effect was also seen in our previous phenomenographic analysis and reflects memorization strategies triggered by familiar problem structures.

To support instructional decision making, we identify nine incorrect categories with a frequency rate greater than 20% (Table XI), five of which incorrect answers exceeded 40%, "Alternative representations" in M1 (55%), "larger implies larger (Ohm's p-prim)" in E3 (52%), "Interference" in E4 (45%), "Incorrect use of laws (Lorentz law)" in M4 (46%), and "Interference" in E5 (47%). These patterns highlight specific alternative conceptions that instructors are likely to encounter when teaching fields and forces in introductory electricity and magnetism courses. Part of the significance of this study lies in the analyses and recommendations, which can serve as valuable resources for physics education researchers and instructors teaching these concepts.

Our findings reinforce the idea that understanding the vector nature of fields is a central yet fragile component of

students' reasoning in electromagnetism [4,7,11,24,31], and the present study shows that students struggle with its abstract representation. Instruction that systematically connects different representations, such as vector diagrams, field-line diagrams, graphs, and symbolic expressions, may help students move beyond surface features. We recommend didactic sequences that include qualitative exercises on converting between representations, supported by tools such as visual simulations, augmented or virtual reality, to make the vector nature of the field more accessible. Emphasis should also be placed on the physical meaning and representation conventions of fields to distinguish them from related concepts, especially from that of force.

A central instructional strategy proposed involves the use of parallel problems that exploit the symmetry between electricity and magnetism described by Maxwell's equations. Prior research and our results support this approach, revealing insights into students' understanding of electric and magnetic interactions, superposition, and field concepts [3–5,14,34]. These parallel problems help highlight differences between similar-looking phenomena, encouraging deeper reasoning and reducing confusion, particularly around commonly conflated ideas like interference.

Although each form was administered to 116 students, this sample size is appropriate for the item-level indices reported here (difficulty, discrimination, and point-biserial) and for the chi-square comparisons of response distributions, because expected counts per option remain above common minimum thresholds. Nevertheless, the modest N per form reduces sensitivity to small differences between contexts; therefore, nonsignificant comparisons should be interpreted as an absence of evidence of a difference at this sample size rather than evidence of equivalence. In addition, because the present study relies on multiple-choice

response patterns, it cannot directly capture students' underlying reasoning or explanatory framing; future work could complement this approach with qualitative methods (e.g., interviews or think-aloud protocols) to better characterize why students differentiate between the electricity and magnetism formulations and how they justify specific distractor selections. Future research could extend this work by validating the instrument with more diverse student populations and examining how targeted instructional interventions informed by these findings affect students' understanding of electric and magnetic fields and forces.

Finally, we would emphasize the need to confront students' prior conceptions, such as overgeneralized rules like the ROS, which may be socially learned rather than scientifically grounded. Strategies such as cognitive conflict, counterexamples, and inverse problems are effective for revealing and addressing these misconceptions [51,65,66]. Additionally, persistent emphasis on underlying physical principles rather than memorized procedures may help students progress toward more expertlike reasoning.

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DATA AVAILABILITY

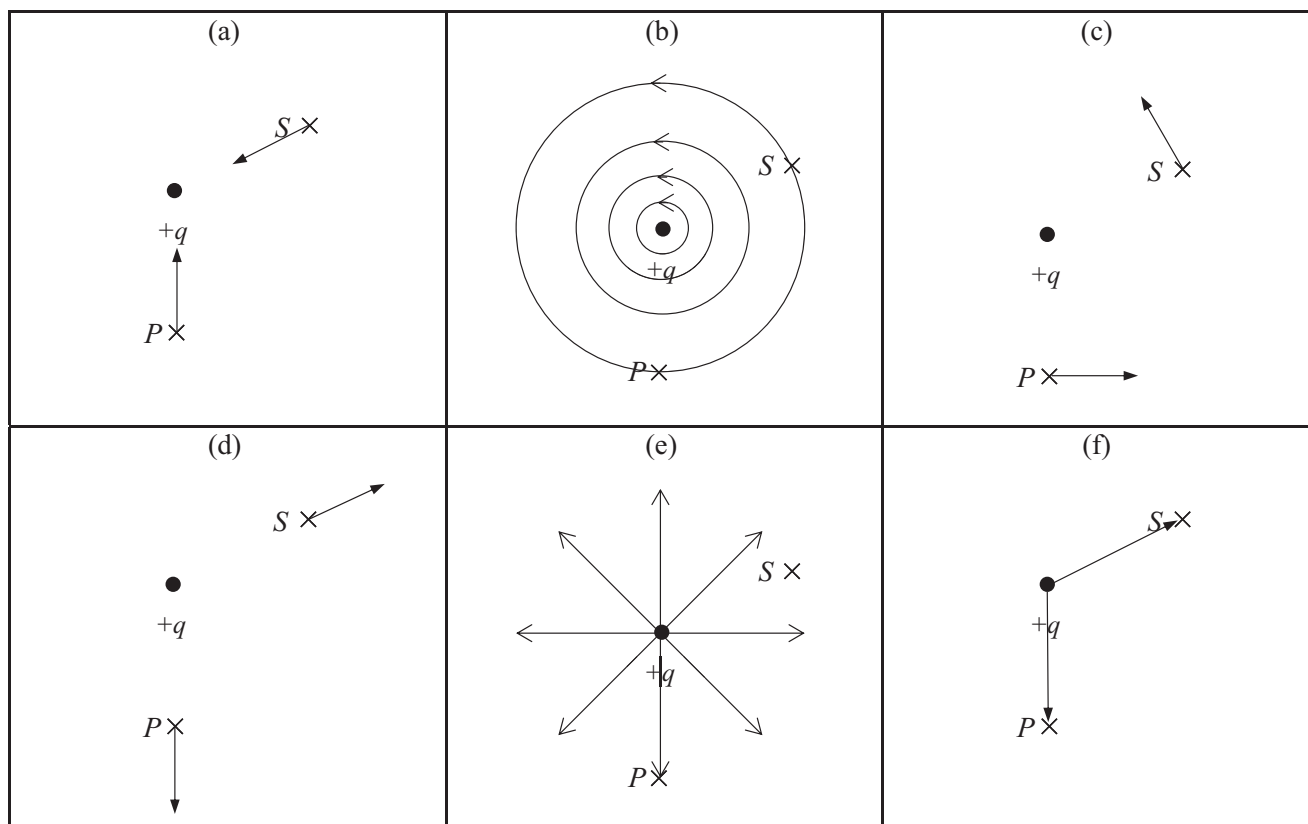
The data that support the findings of this article are not publicly available because they contain sensitive personal information. The data are available from the authors upon reasonable request.

APPENDIX A: ELECTRICITY ITEMS

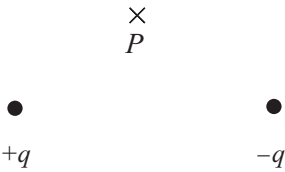
E1. The figure on the right shows a point charge $+q$ in space and two positions P and S located at the same distance from the charge. Which of the options shown below is the best way to represent the electric field at positions P and S ?

 $S \times$

●
 $+q$

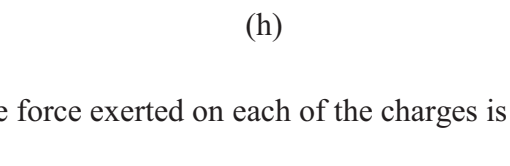
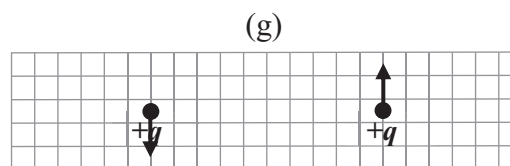
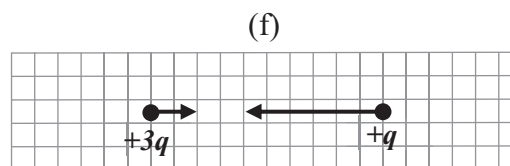
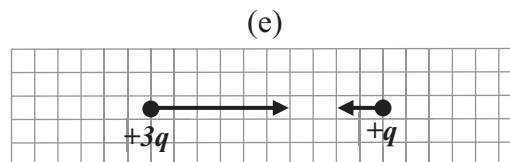
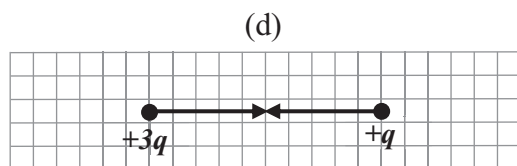
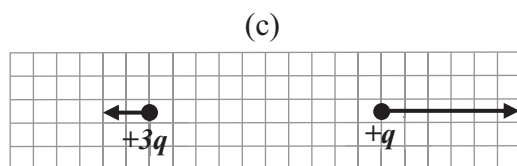
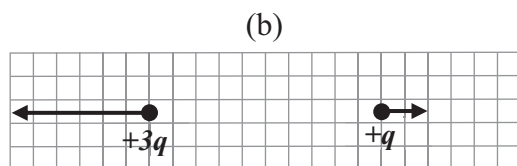
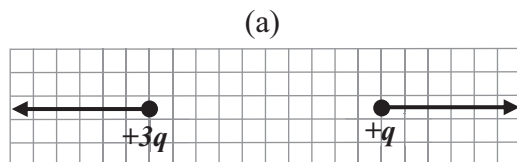
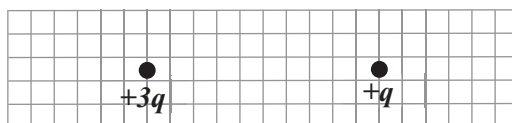
 $P \times$ 

E2. The figure shows two fixed point charges $+q$ and $-q$ and a position P located at the same distance from both charges. Which of the options shown below is the best way to represent the electric field at position P ?



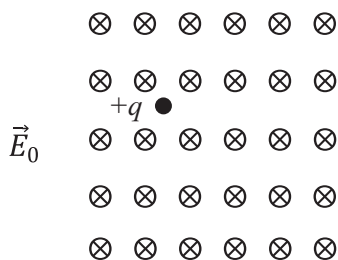
(a) Diagram (a) shows the same setup as the main figure. At point P, there is an 'X' with an arrow pointing vertically upwards.	(b) Diagram (b) shows the same setup. At point P, there is an 'X' with an arrow pointing horizontally to the left.	(c) Diagram (c) shows the same setup. At point P, there is an 'X' with an arrow pointing vertically downwards.
(d) Diagram (d) shows the same setup. At point P, there is an 'X' with two arrows: one pointing towards the $+q$ charge and another pointing towards the $-q$ charge.	(e) Diagram (e) shows the same setup. At point P, there is an 'X' with an arrow pointing horizontally to the right.	(f) The electric field at position P is zero.

E3. The figure shows two fixed electric charges $+3q$ and $+q$. Which of the following options shows the force exerted on each charge due to its interaction with the other?



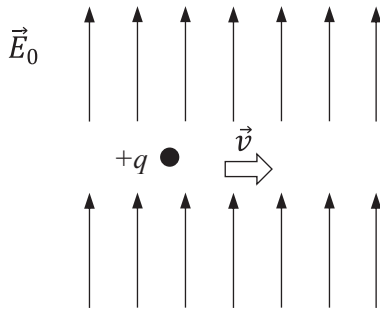
The force exerted on each of the charges is zero.

E4. A charge $+q$ is released from rest in a region with a uniform electric field $\vec{E}_0$ directed into the page, as shown in the figure. Which of the following options represents the direction of the force exerted on the charge $+q$ due to its interaction with the electric field?



- (a) Into the page ($\otimes$)
- (b) Out of the page ($\odot$)
- (c) Left ($\leftarrow$)
- (d) Right ($\rightarrow$)
- (e) Up ($\uparrow$)
- (f) Down ($\downarrow$)
- (g) The force exerted on the charge is zero

E5. The figure shows a point charge $+q$ with velocity $\vec{v}$ located in a region of an electric field $\vec{E}_0$. Which of the following options represents the direction of the force exerted on the charge $+q$ due to its interaction with the electric field?



- (a) Into the page ($\otimes$)
- (b) Out of the page ($\odot$)
- (c) Left ($\leftarrow$)
- (d) Right ($\rightarrow$)
- (e) Up ($\uparrow$)
- (f) Down ($\downarrow$)
- (g) Diagonally up and to the right ($\nearrow$)
- (h) The force exerted on the charge is zero

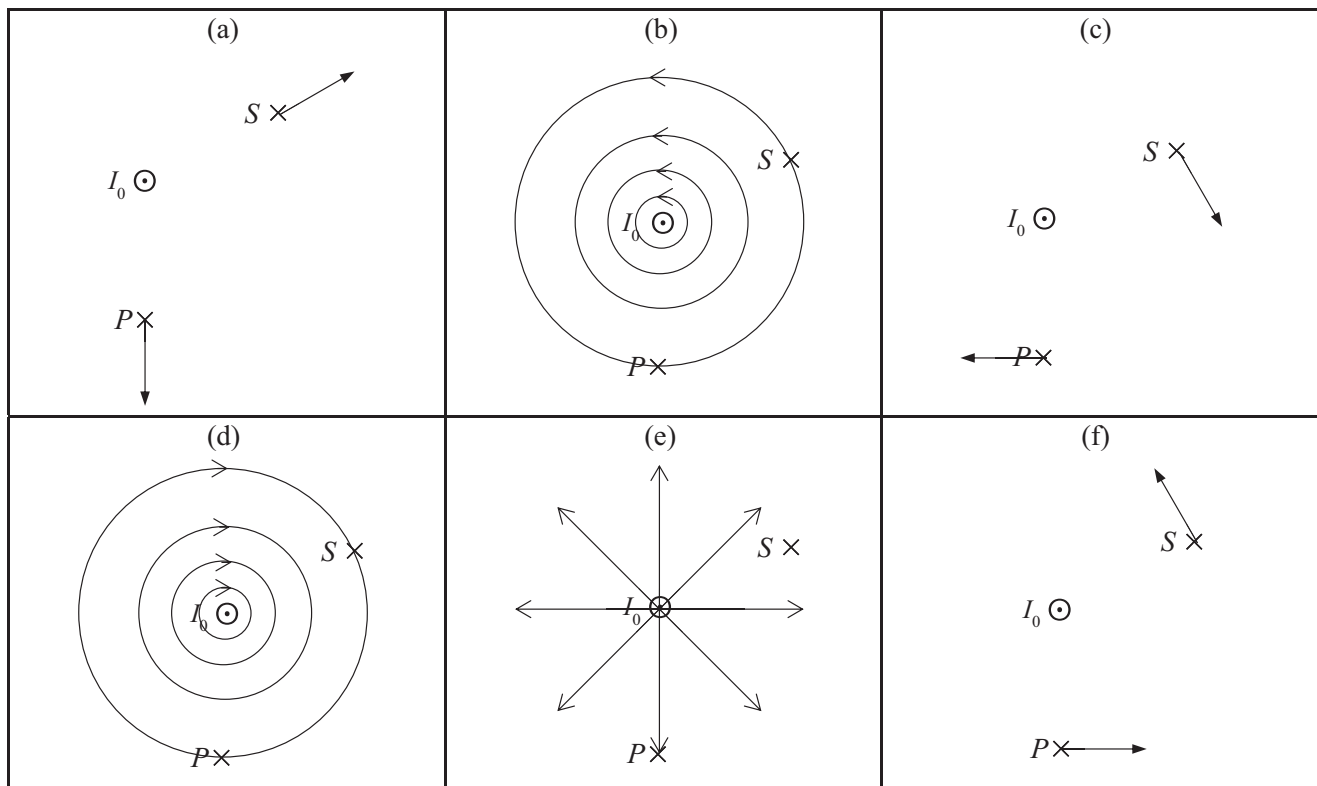
APPENDIX B: MAGNETISM ITEMS

M1. The figure on the right shows a wire that conducts a conventional electric current I_0 in the direction out of the page and two positions P and S located at the same distance from the wire. Which of the options shown below is the best way to represent the magnetic field at positions P and S ?

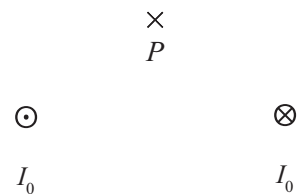
$S \times$

$I_0 \odot$

$P \times$

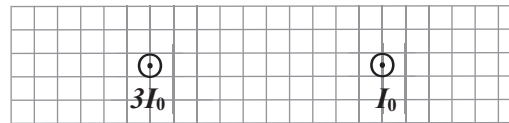


M2. The figure on the right shows two fixed wires that conduct conventional currents I_0 in opposite directions, one out of the page and one into the page, as well as a position P located at the same distance from both wires. Which of the options shown below is the best way to represent the magnetic field existing at position P ?

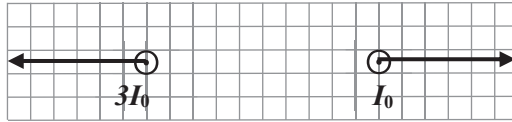


(a)	(b)	(c)
(d)	(e)	(f) The magnetic field at position P is zero.

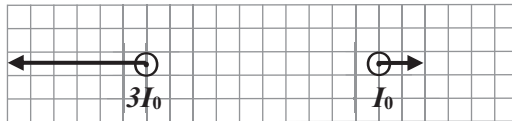
M3. The figure shows two fixed wires that conduct conventional currents $3I_0$ and I_0 in the direction out of the page. Which of the following options shows the force exerted on each wire due to its interaction with the other?



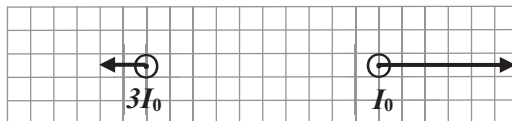
(a)



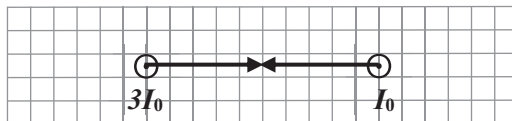
(b)



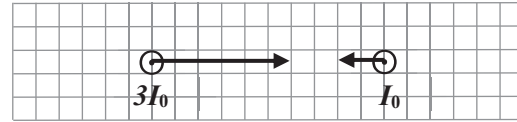
(c)



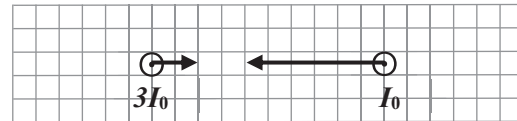
(d)



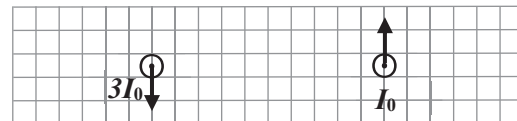
(e)



(f)



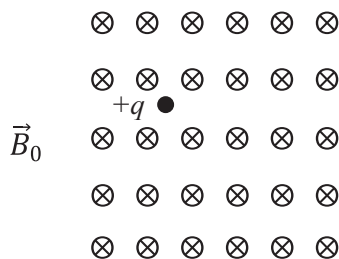
(g)



(h)

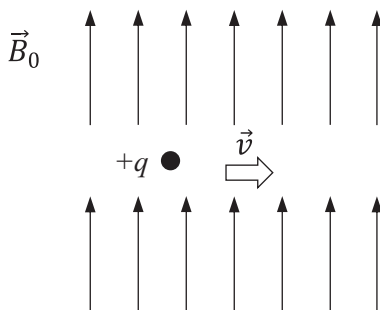
The force exerted on each of the wires is zero.

M4. A charge $+q$ is released from rest in a region of uniform magnetic field $\vec{B}_0$ directed into the page, as shown in the figure. Which of the following best represents the direction of the force exerted on the charge $+q$ due to its interaction with the magnetic field?



- (a) Into the page ($\otimes$)
- (b) Out of the page ($\odot$)
- (c) Left ($\leftarrow$)
- (d) Right ($\rightarrow$)
- (e) Up ($\uparrow$)
- (f) Down ($\downarrow$)
- (g) The force exerted on the charge is zero

M5. The figure shows a point charge $+q$ with velocity $\vec{v}$ that is located in a region of a magnetic field $\vec{B}_0$. Which of the following best represents the direction of the force exerted on the charge $+q$ due to its interaction with the magnetic field?



- (a) Into the page ($\otimes$)
- (b) Out of the page ($\odot$)
- (c) Left ($\leftarrow$)
- (d) Right ($\rightarrow$)
- (e) Up ($\uparrow$)
- (f) Down ($\downarrow$)
- (g) Diagonally up and to the right ($\nearrow$)
- (h) The force exerted on the charge is zero

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