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Investigating Students' Misconceptions in Learning Magnetic Field and Force for Cambodian High Schools

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Abstract

This study aims to analyze students' misconceptions to examine the difficulties students face in learning about magnetic fields and forces in Cambodian high schools. Methodology included both quantitative and qualitative data. Quantitative data were collected from 1,685 high school students who completed a 30-item multiple-choice diagnostic test. Qualitative data was obtained through semi-structured interviews with 30 selected students. The results revealed several recurring misconceptions, including the misapplication of the Right-Hand Rule (RHR), difficulty in translating between two-dimensional diagrams and three-dimensional models, confusion with vector symbols, misinterpretation of magnetic poles, and a misconception of the magnetic force between current-carrying wires. There are five patterns of misconception, including misapplication of the RHR, symbol confusion, misconceptions about magnetic poles, misinterpretation from 2D to 3D representations, and misconceptions concerning magnetic forces between current-carrying wires. In the Cambodian context, a significant number of students had misconceptions about converting and understanding the spatial relationship between the 2D representation and the actual 3D orientation of magnetic fields and forces. Most students struggle with interpreting 2D to 3D diagrams; they are challenged by rotating the object, visualizing orientation changes when the current direction or magnetic field direction changes, interpreting its position from different views, and misapplication of RHR. The implications of this study suggest that instructional strategies should place more emphasis on helping students translate between 2D diagrams and 3D models, supported by explicit training in applying the Right-Hand Rule. Incorporating interactive tools, hands-on activities, and visualization strategies into curriculum design could reduce misconceptions and improve students' conceptual understanding of magnetic fields and forces. For further study, the findings emphasized the need to develop students' ability to visualize 3D representations from 2D diagrams and apply RHR through hands-on activities to enhance conceptual understanding in physics.

Keywords: Magnetic fields and forces, misconceptions, Right-Hand Rule (RHR), 2D to 3D interpretation, Cambodian High School.

1. Introduction

The Cambodian science education framework is outlined in key national policies aimed at improving both instructional quality and innovation. The Education Strategic Plan (ESP) 2024-2028 aims to enhance science and technology education by fostering critical thinking, adopting modern curricula, and establishing Centers of Excellence in higher education (MoEYS, 2024). The government also introduced the National Policy on Science, Technology, and Innovation (STI) 2020-2030 to support overall progress through innovation and national growth. This policy focuses on developing human resources in the STEM workforce, promoting gender equality in science, and cultivating a culture of innovation. Complementing this objective, the STI Roadmap 2030 outlines a detailed implementation plan, emphasizing improved governance, broadening access to STEM education, enhancing research and development, and fostering collaboration between the public and private sectors (National Council for Science and Technology, 2019). Moreover, Cambodia launched the Strategic Plan for Teacher Education Reform 2024-2030, shifting pre-service training to a four-year program and stressing digital literacy and ongoing professional development. These initiatives collectively underscore Cambodia's commitment to enhancing science education, developing a skilled workforce, and promoting an innovative, knowledge-based society (MoEYS, 2025).

In Cambodia's physics curriculum and textbooks, especially those for grades 9 and 12, magnetic fields and forces are key concepts that help students build both scientific understanding and practical skills (MoEYS, 2017; MoEYS, 2018). In Grade 9, students explore magnetic poles, compasses, and how to visualize magnetic fields using iron filings or a compass, with typical activities such as mapping field lines around a bar magnet (MoEYS, 2017). As they advance to upper secondary, textbooks expand to include magnetic fields produced by electric currents and the forces on moving charges and conductors. Students learn to use formulas, such as $\mathbf{F}= q\mathbf{v}\times\mathbf{B}$, to understand relationships and analyze real-world devices, including electric motors, generators, and transformers (MoEYS, 2012). They also see how magnetism applies to everyday technologies, for instance, electromagnets in magnetic separation for flour processing and MRI machines. Magnetic fields are essential in numerous industries, particularly as the requirement for magnetic sensors grows to support applications such as speed measurement, proximity detection, digital compasses, and automation systems. They are also vital in sectors such as transportation, manufacturing, healthcare, and consumer electronics. Additionally, MRI technology is increasingly used in Cambodian medical facilities. Based on the textbook, which discusses the content of magnetic fields and forces, as well as their applications in daily life, the textbook links classroom learning to real-world applications, enhancing scientific literacy and preparing students for STEM careers in Cambodia’s expanding education and technology sectors (MISTI, 2021).

Electromagnetism is a core topic in physics education, and magnetic fields and forces play a key role in the senior high school curriculum as key concepts for grasping the principles of electromagnetism (Fatmaryanti et al., 2017b). Although their importance is recognized, many students struggle to develop an understanding of magnetic fields and forces, mainly due to the abstract and spatially demanding nature of the concept.

Numerous studies have demonstrated that students worldwide consistently hold misconceptions about magnetic fields and forces (Sağlam & Millar, 2006; Kustusch, 2016; Maloney et al., 2001; Galili, 1995). Prior research consistently documents persistent difficulties in magnetic fields and forces, including confusion about field concepts, force directions, and multiple representational use (Fatmaryanti et al., 2017a; Duit & Treagust, 2003; Gagnier et al., 2017; Sorby, 2009). In addition, many learners misapply the Right-Hand Rule (RHR) and struggle with the direction of magnetic force on moving charges, with errors tied to confusion about magnetic field direction and the choice of RHR (Ho et al., 2006; González et al., 2017). By reviewing previous research, misconceptions can be grouped into four main categories: misapplication of the RHR, symbolic confusion, misconception of magnetic poles, and magnetic force between current-carrying wires.

Misapplication of RHR is a common error that students often make when determining the direction of a vector. A significant area of difficulty lies in the correct application of the RHR, which is used to determine the direction of a magnetic field and the force associated with current or motion. For many high school students, one of the most significant challenges in physics is applying the RHR to determine magnetic fields and forces, while also translating concepts from two dimensions (2D) to three dimensions (3D), is one of the most challenging topics for high school students to master in physics (Sağlam & Millar, 2006). The RHR is a visual-spatial strategy that requires learners to align hand gestures with vector directions to predict magnetic forces (Scaife & Heckler, 2010). Numerous studies have found that students misinterpret magnetic forces as acting without direction and incorrectly apply RHR (Kustusch, 2016; Maloney et al., 2001). Students frequently confuse the roles of the fingers and thumb in the RHR, leading to consistent errors in vector orientation (Galili, 1995).

Additionally, symbolic confusion is another well-documented issue. Representations such as the dot (⦿) and cross (⊗), which indicate vectors coming out of the page and going into the page, are often misread and interpreted in reverse by students (Fatmaryanti et al., 2017a). Even high-achieving students tend to misinterpret these symbols, confusing vector directions and resulting in incorrect predictions of magnetic fields and forces (Kustusch, 2016).

Moreover, the misconception of magnetic poles can be isolated, such as the concept of electric charges, leading many students to misunderstand the nature of magnetic fields and dipoles. Students tend to think of magnetic poles as electric charges, which results in misconceptions such as "like poles attract" or "opposite currents attract," even though these notions are scientifically inaccurate (Duit & Treagust, 2003).

Furthermore, the misinterpretation of translating from two-dimensional (2D) into three-dimensional (3D) representations is the most common misconception that students face in learning STEM, Engineering, Mathematics, Science, and physics. Gagnier et al. (2017) demonstrated that students frequently struggle to infer the contents of a 3D object when only a 2D diagram or surface view is provided. They struggle to precisely visualize internal spatial relationships, which can lead to misconceptions or an incomplete understanding of STEM concepts. Additionally, students struggle to visualize the spatial relationships, rotations, and cross-sections of objects in three dimensions when learning engineering with only 2D images or sketches (Sorby, 2009). Students struggled to rely solely on feature mapping and simple visualization because these methods lack organized axes and straightforward features in the study of mathematics (Ho et al., 2006). After that, students are unable to distinguish between 2D and 3D representations, and they incorrectly interpret the positions and shapes of objects (St. John et al., 2001). Changes in viewing angles can change how objects appear, leading errors when students interpret shapes and sizes in science topics. Students must correctly measure the shapes, sizes, spatial arrangements, and positions of objects from different viewpoints (González et al., 2017). This task involves clarifying multiple perspectives, operating virtual objects, and realizing dynamic relationships, skills that can be challenging to master without sufficient guidance.

In the Cambodian context, these misconceptions are further compounded by systemic educational challenges. Physics instruction frequently relies on memorization and a teacher-centered approach, with limited opportunities for students to engage in conceptual reasoning and practical experimentation, and a shortage of teaching and learning materials (Leng et al., 2021; Vann, 2023).

According to the National Assessment in Grade 11 and the Technical Report of Grade 8, students' achievement in the physics subject was below average, with 34.5% and 42.2% of students achieving below average, respectively. This result indicates that there were six topics: Force and Motion (52.0%); Sound (45%); Energy and Electric Power (44.2%); Work, Energy, and Power (37.5%); Straight Motion (36.9%); and Magnetism (34.5%), and among these topics, the magnetism topics is the lowest percentage of correct answers (MOEYS, 2019; MoEYS, 2023). Therefore, magnetism was a topic that presented complicated and abstract concepts for students to understand, and it is part of the challenges students face in misconceptions about learning magnetic fields and forces.

Despite a growing body of international and Cambodian literature, there is limited empirical evidence about how misconceptions about magnetic fields and forces are established in the Cambodian high school context. Most existing studies focus on Western or Asian education systems, which have different curricular and instructional traditions. This gap in the literature makes it difficult to generalize findings about approaches, resource availability, and emphasis placed on abstract reasoning skills within the national curriculum. Therefore, this study fills an important gap by examining the misconceptions that high school students have about magnetic fields and forces, particularly their struggles with transitioning between two-dimensional (2D) and three-dimensional (3D) representations.

The theoretical framework of this study is based on the multiple representations and conceptual change theory. The multiple representations framework emphasizes the importance of having students utilize symbols, drawings, diagrams, and pictures to foster a deeper understanding. According to conceptual change theory, misconceptions are not merely simple errors in answers but instead represent underlying cognitive frameworks that need to be confronted, reorganized, and replaced through appropriate teaching approaches and learning resources. When teachers identify and address these misconceptions directly, they guide students in rethinking and refining their flawed mental models into scientifically valid concepts.

To address this gap, this study aims to analyze students' misconceptions in order to examine the difficulty of learning magnetic fields and forces in high school.

To achieve the above purposes, the question will be addressed below.

What types of misconceptions do high school students have in learning about the magnetic field and force?

2. Methodology

This study was conducted in accordance with ethical research standards. Informational consent was obtained from all participating students and, where necessary, from their parents. This research has ethics committee approval from Hiroshima University, dated June 26, 2024, and number HR-ES-001818.

2.1 Research Design

This study examined an explanatory mixed-methods design to investigate students' difficulties in learning about magnetic fields and magnetic force (Creswell & Creswell, 2018). The design integrated quantitative and qualitative approaches to explore students' misconceptions about magnetic fields and forces. In the first phase, quantitative data were collected through a test to find out correct and incorrect responses among students. These results informed the qualitative phase, where participants were selected based on their quantitative performance, categorized as high, medium, or low scores. Interview questions were then conducted to determine the type of misconceptions. This research consisted of two phases of data collection, with Phase One using a test and Phase Two using a semi-structured interview. First, during data collection, the quantitative findings shaped the qualitative sampling and protocol. Second, during interpretation, qualitative insights were used to explain and contextualize quantitative trends. This iterative process ensured that both strands of data complemented each other, providing a richer understanding of students' misconceptions.

2.2 Research Participants

The participants in this study were high school students in grade 12 enrolled in the 2023-2024 school year, as designated by the school principal, using a convenience sampling method. This research was conducted with 14 high schools in urban and suburban areas of Phnom Penh City, involving 1,685 students who voluntarily completed a 30-item diagnostic test on magnetic fields and forces in the quantitative phase of the study. This number was determined based on the total population available. The students were drawn from four urban schools across four districts in urban and 10 suburban schools selected from 10 suburban districts, representing a diverse range of academic performance levels and school contexts. This sample approach ensured both sufficient statistical reliability and representation of the target population.

Semi-structured interviews were conducted with 30 12th-grade high school students from the same schools to collect qualitative data. The participants were chosen from the larger sample using purposive sampling. The chosen criteria were based on students' achievement levels on the diagnostic test, which included high, medium, and low scores, as well as representation from both urban and suburban schools. Specifically, the sample consisted of 10 students with high scores, 10 with medium scores, and 10 with low scores. This selection ensured the representation of a broad spectrum of reasoning approaches, from well-formed conceptual understanding to frequently observed Misconceptions.

The interview was conducted in Khmer, the students' native language, to promote natural expression and lower language barriers. The interviews were videotaped and transcribed verbatim in Khmer. A professional, bilingual translator then translated the transcripts into English. To ensure reliability and consistency, a second bilingual researcher reviewed the English transcripts along with the original Khmer versions, resolving any inconsistencies through discussion and collaboration. This method helped reduce potential biases and maintained the authenticity of students' responses in the qualitative analysis.

2.3 Research Instrument

The instruments used in this study are survey tests and semi-structured interviews, which consist of a 30-item multiple-choice test. This test was developed using the Grade 12 physics syllabus and textbooks (MoEYS, 2012; MoEYS, 2018) and adapted from Chandralekha and Jing (2012). The multiple-choice test was used to assess the percentage of correct and incorrect options. The test items covered five topics related to magnetic fields and forces, including the application of the RHR and Left-Hand Rule (LHR) to determine the direction of magnetic force, magnets, the magnetic field due to a long straight wire, the interaction between two parallel wires, and charged particles moving in a uniform magnetic field.

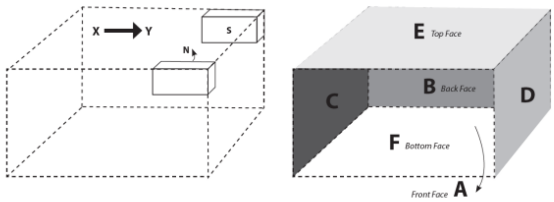
To ensure a thorough understanding among students, the diagnostic test consisted of 30 items covering five topics related to magnetic fields and forces. The distribution of these items was uneven, with the topic "The Magnet" receiving a greater number of questions. This was a deliberate choice, emphasizing its importance in the national curriculum and its role as a foundational concept for later topics such as magnetic field direction, current-carrying conductors, and the application of the RHR. Furthermore, the prior studies above also highlighted the persistence of misconceptions in this topic, justifying the inclusion of additional items to capture their variety and depth. This topic is the basic topic for magnetic fields and forces.

Table 1: Topics and Number of Test Items

No	Topics	Item Number	Number of Items
1	The application of the RHR to determine the magnetic force direction	1, 2, 3, 4,5	5
2	The Magnet	6,7,8,9,10,11,12,13,14	9
3	The magnetic field due to a long straight wire	15,16,17,18,19	5
4	The interaction between two parallel wires	20,21,22,23,24	5
5	Charged particles moving in a uniform magnetic field	25,26,27,28,29,30	6
	Total		**30**

According to the test item in Table 1, the following items test relate to each topic.
For topic 1: the application of the RHR to determine the magnetic force direction.
The question is: the particle moves into the magnetic field, as shown in the figure below. Identify the direction of the magnetic force on the cuboid face.

A. Front face
B. Back face
C. Left face
D. Right face
E. Top face
F. Bottom face



This multiple-choice question is designed to assess students' understanding of how to apply procedural knowledge of the RHR to determine the direction of the magnetic force. This item consists of a diagram of a cuboid with labelled faces and vectors representing the particle's motion and magnetic field, prompting students to identify which face the force vector points toward. The item is specific misconceptions frequently found in electromagnetism learning, such as misapplication of the RHR, confusing the direction of current with velocity.

Topic 2: The magnet

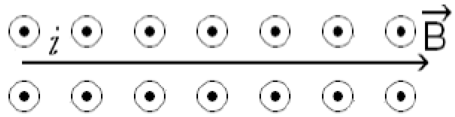
The question is: What happens when the two north poles of a magnet are placed together?

A. They repel.
B. They attract.
C. They cancel each other out.
D. The strength of the magnet is doubled.
E. None of the above

This multiple-choice question is designed to assess students' understanding of the basics of magnetic interactions, specifically the behaviour of magnetic poles. This item assesses conceptual knowledge within the topics of magnetic fields and forces, focusing on the principle that like poles repel each other while opposite poles attract. The distractors are constructed to reflect common misconceptions about the characteristics of magnetism.

Topic 3: The magnetic field due to a long straight wire.

The item is a very long straight wire carrying a current i to the right (see figure below), placed in a uniform magnetic field $\vec{B}$ directed out of the page.



What is the direction of the force on the wire due to the magnetic field $\vec{B}$?

A. To the right (→)
B. Upward (↑)
C. Downward (↓)
D. Out of the page (⊙)
E. Into the page (⊗)

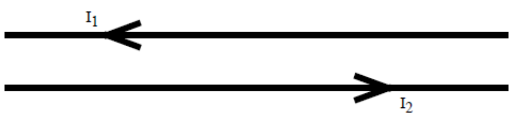
This item evaluates students' ability to determine the magnetic field of a long straight wire and to determine the direction of the magnetic force on a current-carrying conductor placed in a uniform magnetic field. The incorrect options are carefully selected to reflect common student errors, such as confusing current direction with field direction, reversing the cross product, and misinterpreting symbols indicating "into" and "out of the page."

Topic 4: The interaction between two parallel wires.

Two long, parallel wires carry currents in opposite directions. Wire 1 carries conventional current to the left, and wire 2 carries conventional current to the right.

The magnetic force on two wires is:

A. Attract each other.
B. Repel each other.
C. Both attract and repel.
D. Neither attract nor repel.
E. None of the above



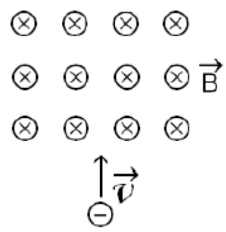
This item test evaluates students' conceptual understanding of the magnetic interaction between two long parallel current-carrying wires. Specifically, it focuses on the direction of the magnetic force resulting from currents flowing in opposite directions.

Topic 5: Charged particles moving in a uniform magnetic field.

An electron with an initial velocity $\vec{v}$ enters an evacuated region with a uniform magnetic field $\vec{B}$, directed into the page. The velocity of the electron is perpendicular to the magnetic field as shown.

Ignoring the gravitational force, how many forces act on the electron after it enters this region?

A. One, the force of the electron's initial velocity.
B. One, the magnetic force.
C. Two, the force of the electron's initial velocity and the magnetic force.
D. Two, the electric force due to the charge of the electron and the magnetic force.
E. No force acts on the electron.



This multiple-choice question assesses students' conceptual understanding of the magnetic force on a charged particle, specifically in the context of an electron entering a uniform magnetic field perpendicular to it. The distractor options are designed to show common misconceptions, such as treating velocity as a force, assuming an electric force acts simply because the particle is charged or concluding that no force acts in uniform fields.

The diagnostic test was created based on common student misconceptions found in the literature. To verify content validity, five physics experts reviewed the test, evaluating the items for scientific accuracy, clarity, and consistency with the curriculum. Their feedback was used to make revisions. The test was then piloted with 35 high school students to ensure the clarity, comprehensibility of the wording, and reliability of each item. To measure clarity and reliability, the tests were administered to identify which items students struggled to understand, both in terms of meaning and figures. We then revised them based on their feedback. Moreover, the test items were piloted with a Cronbach's Alpha coefficient of 0.9, meaning they are reliable. The most frequently selected incorrect answers were analyzed. For semi-structured interviews, the questions were constructed to reflect specific misconceptions, including the misapplication of RHR, misinterpretation of 2D to 3D, symbol confusion, the magnetic pole misconception, and the misconception of the magnetic force between current-carrying wires. Three high school teachers validated the questions to ensure that students understood them. Then, revise based on the feedback from reviewers. The semi-structured interview began with guided questions that ranged from general to in-depth, reflecting the above misconceptions.

2.4 Data Collection Procedure

Data collection followed a mixed-methods approach, integrating both quantitative and qualitative phases. In the first phase, a 30-item multiple-choice diagnostic test was given in a classroom setting during regular school hours. Students worked independently and were allotted 50 minutes to complete the test. The researcher and the teacher administered and collected data during the tests. After that, the researcher compiled the data for statistical analysis, focusing on the percentage of students selecting each option, with a particular emphasis on identifying the most common incorrect choices.

Following the quantitative analysis, a purposive sample of 30 students was selected for semi-structured interviews, which lasted approximately 40 minutes. Based on their test responses, students were selected to represent a diverse range of answer patterns, including both correct and incorrect responses. The interviews were conducted in a quiet place, in a face-to-face setting, to encourage open and reflective discussions.

Before each interview, students were informed about the session's purpose, and their consent was obtained to video-record the discussion for research. Each interview began with the presentation of selected multiple-choice questions that the students had already answered. Students were then asked to explain why they used certain concepts to reach their decision. Students were asked to explain their reasoning for specific test items, describe how they used the RHR, translate 2D to 3D, interpret magnetic poles, interpret symbols, and explain the magnetic force between current-carrying wires. Video recordings of the interviews were made and then transcribed for analysis.

2.5 Data Analysis

Quantitative data were analysed to determine the selection frequency and percentages for each response option and to evaluate student performance. Special attention was given to the percentages of correct and incorrect responses to highlight easier and more difficult items based on conceptual understanding. Then, the percentage of the most chosen incorrect option per item was analysed to determine the prevalence of specific misconceptions. Items are grouped based on conceptual skills (for instance, applying the Right-Hand Rule, interpreting 2D to 3D, and understanding symbol notation) to identify patterns of misunderstanding across topics. The diagnostic interpretation was examined, and items with low correct response percentages and high incorrect response selection indicated the misconceptions associated with each item, which informed the themes explored in the qualitative data.

Qualitative data from semi-structured interviews were reported to gain deeper insight into students' conceptual understanding and misconceptions. To classify the misconceptions, a qualitative approach was used, combining deductive and inductive analysis. First, broad categories of misconceptions were identified based on findings from existing physics education literature. These categories included difficulties with the Right-Hand Rule, vector notation, magnetic poles, translating between 2D and 3D representations, and magnetic forces between current-carrying wires. The interviews were purposed to explore students' reasoning for their selected responses and uncover the thought processes behind them, particularly in cases where misconceptions were apparent. Each interview was video recorded and subsequently transcribed into a written document.

During the analysis of students' responses, the data were coded according to these predefined categories, while also remaining open to emerging patterns. A qualitative thematic analysis was conducted by using the written transcripts derived from the recordings. Coding procedures were guided by both pre-identified categories, such as types of misconceptions identified in the literature, and emergent themes that arose during the interviews. The coding process involved several steps: Step 1: watching and reviewing video recordings and reading transcripts to become immersed in the data. Step 2: generating descriptive codes related to specific misconceptions and reasoning patterns. Step 3: Grouping codes into broader themes such as symbolic misinterpretations, misapplication of RHR, and confusion about magnetic poles. Step 4: Interpreting themes to the research questions and comparing them with existing literature. This analysis provided valuable qualitative insights that complemented the quantitative item analysis, leading to a deeper understanding of students' specific misconceptions in electromagnetism. This method enables students to confirm pre-existing misconceptions and identify context-specific difficulties, particularly the significant challenges that Cambodian students face when translating 2D representations into 3D orientations.

3. Results and Discussion

3.1 Results

The results from this data identified the percentage of students who chose the correct and the incorrect responses for each item.

In Table 2, the analysis of student responses to multiple-choice items reveals notable variations in performance across questions when choosing the most incorrect responses. There were twenty-two out of 30 items, students chose the most incorrect responses such as items 1, 2, 3, 4, 5, 10, 11, 12, 13, 16, 17,18, 20, 21, 22, 23, 24, 25, 26, 27, 28, and 30, on the topics of the application of the RHR to determine the magnetic force direction, the magnet, the magnetic field a long straight wire, the interaction between two parallel wires, and charged particles moving in a uniform magnetic field respectively. For example, item 12 showed the highest percentage of incorrect responses (46%), and compared with the correct response, only 15% of respondents answered correctly. Additionally, item 3 had the highest percentage of incorrect responses at 30%, but the correct response was only 15%. In many cases, incorrect answers were concentrated around specific incorrect choices; for instance, in item 3, 30% of students selected option C, which had an incorrect response twice that of the correct answer.

Table 1: The percentage of students who choose the correct and the incorrect responses

Item No	Percentage (%) of students' choice in each response						The Correct Response (%)	The Most Incorrect Response (%)
	A	B	C	D	E	F		
1	14	18	7	12	39	10	E. 39	B. **<u>18</u>**
2	19	20	8	23	18	12	A. 19	D. **<u>23</u>**
3	14	11	30	15	20	10	D. 15	C. **<u>30</u>**
4	8	16	16	19	18	22	F. 22	D.**<u>20</u>**
5	25	13	16	17	9	20	A. 25	F. **<u>20</u>**
6	23	4	56	7	10		C. 56	A. 23
7	84	12	3	1	0		A. 84	B.12
8	80	8	4	8	1		A. 79	B. 8
9	6	81	10	3	1		B. 80	C. 10
10	24	48	7	18	2		B. 48	A. **<u>25</u>**
11	9	9	29	37	15		D. 37	C. **<u>29</u>**
12	19	46	15	14	6		C. 15	B. **<u>46</u>**
13	30	26	24	11	9		C. 24	A. **<u>30</u>**
14	15	16	50	13	5		C. 50	B.17
15	11	14	14	56	4		D. 56	B. 15
16	27	20	22	23	9		C. 21	A. **<u>27</u>**
17	24	15	35	11	15		A. 24	C. **<u>35</u>**
18	36	26	27	11	0		A. 36	C. **<u>27</u>**
19	16	59	12	5	8		B. 59	A. 16
20	26	47	8	16	3		B. 47	A. **<u>26</u>**
21	32	28	13	11	15		A. 32	B. **<u>29</u>**
22	17	27	19	15	22		C. 19	B.**<u>27</u>**
23	13	20	22	22	23		B. 20	E. **<u>23</u>**
24	17	33	21	21	8		B. 33	D. **<u>21</u>**
25	21	30	29	16	6		B. 29	C.**<u>29</u>**
26	9	39	16	26	11		E. 11	B. **<u>39</u>**
27	29	33	18	14	7		A. 28	B. **<u>33</u>**
28	24	18	25	16	17		C. 25	A. **<u>24</u>**
29	63	17	13	7	0		A. 63	B. 17
30	21	25	23	20	10		B. 25	C. **<u>23</u>**

These quantitative results indicated that the test items yielded incorrect responses in more than 50% of the total, including the application of RHR to determine the direction of the magnetic force, the magnetic field of a straight wire, the interaction between two parallel wires, and the motion of charged particles in a uniform magnetic field. Based on these quantitative results, students were interviewed to find the reason why they chose the most incorrect responses.

Table 3 presents the reasons students chose the most incorrect response and identifies the themes underlying these reasons, which highlight the misconceptions in learning about the context of magnetic fields and forces.

Table 2: The Correct, Incorrect responses and the themes

Students Number (ST)	Correct responses	Most Chosen Incorrect Responses	Themes
ST5	Raising four fingers in the direction of velocity is upward, the thumb is the direction of magnetic force to the left and turning the four fingers in the direction of the magnetic field into the page.	Use RHR by raising four fingers in the direction of velocity upward, then the thumb in the direction of magnetic force to the right and turning the four fingers in the direction of the magnetic field out of the page.	**RHR Misapplication**
ST12	The four fingers are rotated to the right as the direction of current, and the thumb is the direction of the magnetic field into the page.	The four fingers are rotated to the right as the direction of the magnetic field, and the thumb is downward.	**Misinterpret from 2D to 3D**
ST5	The thumb is the direction of current (dot sign) out of the page, and the cross sign is also the direction of current into the page.	The thumb is the direction of current (dot sign) into the page, the cross sign is the direction of the magnetic field out of the page and fold the four fingers to the right.	**Symbol Confusion**
ST25	- The direction of the magnetic field moved from the North to the South pole, and the direction of the magnetic force is upward. - The magnets have the same pole repel each other, and opposite poles attract each other.	-The direction of the magnetic field moved from South to North, then the direction of the magnetic force to the right. -The magnet has the same poles attracting each other. The magnets have opposite poles repelling each other.	**Magnetic Pole Misconceptions**
ST2	Two wires are crossing in the opposite direction of the current, and the magnetic force of both wires attracts each other.	In the opposite direction of the current across the two straight wires, the magnetic force of both repels them.	**Magnetic Force Between Current-Carrying Wires Misconception**

Note. ST=Students Number (e.g., ST5=Student number 5; ST2=Student number 2; ST12=Student number 12; ST25=Student number 25). RHR=Right-Hand Rule

The results indicated that the most incorrect student responses shared several recurring patterns, including (1) RHR misapplication, (2) 2D to 3D misinterpretation, (3) symbol confusion, (4) misconceptions about magnetic poles, and (5) a misconception about the magnetic force between current-carrying wires.

Students' misconceptions about the RHR in the magnetic field and force.

One of the most common misconceptions involved the misapplication of the RHR, where students often reversed the direction of velocity, magnetic field, and magnetic force. They explained that,

> *"Using four fingers in the direction of XY and turning four fingers upward, the thumb is the direction of the magnetic force to the right. Use RHR by raising four fingers in the direction of velocity upward, then the thumb in the direction of magnetic force to the right and turning the four fingers in the direction of the magnetic field out of the page."*

Students’ misconceptions about translating from 2D to 3D in the magnetic field and force.

The second misconception is that students struggle to visualize how the vectors are oriented in three-dimensional space. A significant issue was the misinterpretation of two-dimensional diagrams into three-dimensional models, and many students struggled to correctly align their hand gestures or understand the direction of magnetic force when applying physics laws. They claimed that,

> *“The circular direction is rotated to the right, so the magnetic field is also to the right. In the figure, the direction of the current is to the right; therefore, the direction of the magnetic field is also to the right.”*

Students' misconceptions about confusion with symbols in the magnetic field and force.

The third misconception was confusion with symbolic notation, particularly the dot (⦿) and cross (⊗) symbols used to represent vector directions going out of or into the page. Students often misinterpret these symbols, which leads to mistakes in determining the direction of the current or magnetic field. They clarified,

> *“The cross sign is the current, and the dot is the magnetic field. The cross is the direction of the magnetic field, and the dot is the direction of the current. The thumb is the direction of current (dot sign) into the page, the cross sign is the direction of the magnetic field out of the page, and fold the four fingers to the right.”*

Students’ misconceptions about magnetic poles.

Another misconception is the misconception of magnetic poles, a fundamental principle, such as the claim that like poles attract and unlike poles repel, which highlights deeply rooted misconceptions. Students illuminated that,

> *"The opposite direction of the current attracted each other. The direction of the magnetic field moved from South to North, then the direction of the magnetic force to the right. The magnet has the same poles attracting each other. The magnets have opposite poles repelling each other.”*

Students’ misconceptions about the magnetic force between current-carrying wires.

The last issue is the misconception of the magnetic force between current-carrying wires. Several responses reflected an incomplete understanding of current interaction, where students recalled relevant concepts, such as magnetic force attraction between wires, but were unable to explain them clearly and apply them accurately. Students explained that,

> *“The opposite direction of the current repels each other, and the same direction of the current attracts each other.”*

3.2 Discussion

This study investigates students’ misconceptions to examine their difficulties in learning about magnetic fields and forces, identifying several key issues. The quantitative data, supported by qualitative interviews, demonstrated misconceptions, particularly in the areas of RHR application, translating from 2D to 3D, interpreting symbols, understanding magnetic poles, and understanding magnetic forces between current-carrying wires.

Based on Table 4, to understand why students have misconceptions about magnetic fields and force, we conducted interviews with them. These provided more profound insights into the reasoning behind their answer choices, finding consistent themes of misconception.

This study revealed five prevalent areas of students' misconceptions related to magnetic fields and forces: RHR misapplication, misinterpretation from 2D to 3D, symbol confusion, magnetic pole misconception, and misconception about the magnetic force between current-carrying wires.

A dominant theme was the misapplication of the RHR, evident in items 1, 2, 3, 4, 5, 16, 17, 18, 21, 22, and 27, where the student placed their fingers incorrectly. This study aligns with Özdemir & Coramik (2018) and Kustusch (2016), who mentioned that students often attempted to use the RHR but placed their fingers incorrectly and misunderstood the meaning of each finger. Then, students chose the incorrect direction of the magnetic forces, and as a result, they were unable to answer these tests correctly. Ramful et al. (2023) noted that students have difficulty coordinating their fingers accurately to follow the arranged hand orientations. By comparing this study with those of three authors who shared the same misconception, it is evident that students also struggle to align the three fingers properly. For example, applying the correct perpendicular relationship between the thumb, forefinger, and middle finger is challenging, especially without guided practice.

Table 4: The themes and Students' misconceptions

Themes	Items	Most Chosen Incorrect Option (% Selected)	Misconception
RHR Misapplication	1, 2, 3, 4, 5, 16, 17, 18, 21, 22, 27	Often 18 – 35%	Incorrect finger placement or role confusion in RHR
Misinterpret from 2D to 3D	2, 4, 10, 17, 18, 22, 23, 27	Often 19 – 35%	Cannot mentally visualize vector directions from diagrams
Symbol Confusion	11,16, 17, 18, 22, 23	Often 23 – 35%	Misread "⦿" and "⊗" as direction of magnetic field or current.
Magnetic Pole Misconceptions	2, 7, 8, 9	Often 8 – 23%	Thoughts like poles attract are misunderstood in interaction Confused about the direction of the magnetic field, which moved from south to north.
Magnetic Force Between Current-Carrying Wires Misconception	20	26%	Thought opposite currents attract each other.

Additionally, symbol misinterpretation was a common misconception. Items 11, 16, 17, 18, 22, and 23 revealed that many students were confused about the meanings of the dot (⦿) and cross (⊗) notations. This finding is supported by Kustusch (2016) who demonstrated that students struggled to interpret the symbols used to denote the direction of vectors, such as the (⊗) symbol, which represents vectors going into the page, whereas the (⦿) symbol indicates vectors coming out of the page. Hau et al. (2018) found that students misapply vector signs and make errors in writing equations, indicating difficulties with proper symbolic notation and resolution. They are confused regarding formulas and symbols, such as why specific symbols are written in particular ways and how to interpret them in physical terms. The findings from this study are consistent with previous research, such as Kustusch (2016) and Hau et al. (2018) confirming that symbol misinterpretation is a prevalent challenge in understanding vector direction. Consistent with these studies, many students in the current sample demonstrated confusion when interpreting the dot (⦿) and cross (⊗) symbols.

Misconceptions regarding magnetic poles were identified in items 2, 7, 8, 9, and 20, where some students believed that like poles attract each other and opposite poles repel from each other, challenging established physical laws. This finding aligns with Sağlam and Millar (2006) who noted that students perceive magnetic poles as charges, believing that magnetic poles exert forces on charges in the same way as electric charges. In addition, Scaife and Heckler (2010) presented that students often hold misconceptions about the direction of the magnetic field, believing it points from the south to the north pole, which leads to systematic sign errors, especially when their understanding of the magnetic field direction from the poles is incorrect. Like these earlier studies, students confuse magnetic poles with electric charges, leading to incorrect assumptions about attraction and repulsion. Then, they misunderstood how magnetic poles behave and interact with each other.

Moreover, the magnetic force between current-carrying wires is a misconception. In item 20, 26% of students believed that the opposite direction of the currents across parallel wires attract each other, which is incorrect. This study is supported by Jelicic et al. (2017), who showed that students recognize that a current-carrying wire produces a magnetic field but struggle to accurately describe the magnetic field or related electrical effects of magnetic phenomena. They were also confused about the distinction between magnetic and electric forces, which made it difficult for them to determine the direction of magnetic forces. This misconception likely arises from confusing the rules of magnetic interaction with those of electrostatics. In electrostatics, unlike charges attract one another, and like charges repel each other. Following the direction of the magnetic force, parallel currents attract in the same direction, while opposing currents repel in the opposite direction.

Among the five identified themes, the difficulty in interpreting 2D diagrams into 3D representations was particularly significant. Many students struggled to mentally rotate objects, tracked orientation changes when current or field directions were altered, and correctly applied the RHR across different viewpoints. Previous research has highlighted similar challenges, linking them to broader learning (St. John et al., 2001; Sorby, 2009; Gagnier et al., 2017; González et al., 2017).

According to previous international studies on students' misconceptions in learning magnetic fields and forces, which have widely reported issues such as RHR misapplication, symbol confusion, magnetic poles misconception, and misconceptions about magnetic force between current-carrying wires, they rarely mention misinterpretations from 2D to 3D diagrams. However, this study found that in the Cambodian context, a significant number of students struggled to convert and understand the spatial relationship between 2D representations and the actual 3D orientation of magnetic fields and forces. The findings reinforce these results but also suggest that this difficulty is exacerbated by materials and interactive visualizations, especially in Cambodia, where it is a unique contextual factor influencing students' understanding of learning magnetic fields and forces. This is possibly linked to limited exposure to spatial reasoning activities and a lack of 3D learning materials in physics education. To fill this gap, developing teaching materials, hands-on experiments, and teaching methods can enhance students' spatial reasoning, such as using 3D models and hands-on experiments with RHR, which is essential. Improving students' skills in translating between 2D and 3D representations can help teachers reduce misconceptions and promote a deeper understanding of magnetic fields and forces in classroom instruction.

4. Conclusion

This study investigated the misconceptions that Cambodian high school students encounter in learning magnetic fields and forces. The findings revealed five patterns of misconception, including misapplication of the Right-Hand Rule (RHR), symbol confusion, misconceptions about magnetic poles, misinterpretation from 2D to 3D representations, and misconceptions concerning magnetic forces between current-carrying wires. According to the above results, four of the five misconceptions were consistent with findings from previous research. However, this study found that in the Cambodian context, a significant number of students had misconceptions about converting and understanding the spatial relationship between the 2D representation and the actual 3D orientation of magnetic fields and forces. Most students are misinterpreting 2D to 3D illustrations; they are challenged by rotating the object, visualizing orientation changes when the current direction or magnetic field direction changes, interpreting its position from different views, misunderstanding vector directions, and misapplication of RHR. Therefore, this misconception affected students' understanding of magnetic fields and force, indicating gaps in conceptual knowledge that can hinder students' progress in learning physics.

This study has certain limitations. First, the study was conducted with a specific group of Cambodian high school students, which limits the scope of the findings that can be applied to students in different contexts and regions. Secondly, data collection mainly relied on written assessments and interviews, which did not fully capture students' practical skills in performing experiments within an actual classroom environment. For further study, the findings emphasized the need to develop students' ability to visualize 3D representations from 2D diagrams and apply RHR through hands-on activities to enhance conceptual understanding in physics.

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