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Alternative to the right-hand rule: Farah's method

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Abstract

Right-hand rule (RHR), the conventional tool to establish directions of magnetic field and force in electromagnetism, is hard to use because it involves hand motions and three-dimensional visualisation. This paper presents an alternative approach, called Farah's Method, using rotation of Cartesian coordinate axes rather than hand movements, so students can learn it more easily and with less mental burden, as the proposed method is based on the rotation between the axes.. A challenge encountered in this study was the lack of available resources addressing an alternative approach to the right/left-hand rules. In a quasi-experimental study involving 60 secondary school students, we compared Farah's Method to the RHR through pre- and post-tests with conceptual and problem-solving activities, as shown in Figures 11-13. Under the Farah's Method condition, there were significantly improved post-test scores (80.47% vs. 61.27%, $p < 0.001$), better problem-solving accuracy (87.63% vs. 66.87%), shorter response latencies (35.87 s vs. 53.12 s), and lower self-reported cognitive load (overall rating: 4.31 vs. 3.70). These results draw attention to the method's capacity to simplify vector analysis into concise, significant aspects and foster conceptual understanding. This method is also compatible with learning technologies such as PhET simulations and virtual reality interfaces, where coordinate rotations can be dynamically visualised, making it easier to implement in digital learning environments. This approach has future uses in STEM fields such as mechanics and engineering and offers an accessible, scalable pedagogy for overcoming spatial reasoning obstacles. The research implies that Farah's Method is preferable to the RHR with excellent prospects for revolutionising electromagnetism teaching via technology-enhanced learning.

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Keywords: Farah's Method, electromagnetism, spatial reasoning, STEM pedagogy, physics education, Cartesian coordinate rotations

Introduction

The right-hand rule is a fundamental physics teaching tool that allows students to determine the direction of magnetic forces on moving charges and current-carrying wires, and magnetic field patterns produced by electric currents (Serway & Vuille, 2013). Used extensively in physics textbooks, the technique provides a graphical representation of vector relationships in three-dimensional space (Young, et al., 2012). However, learners are unable to correctly apply the right-hand rule because they face challenges coordinating spatial relation visualisation, hand orientation, and finger placement. This leads them to generate incorrect force or field predictions, and consequently, electromagnetism misconceptions emerge (Giancoli, 2020). For example, students may misalign their fingers or fail to map directions mentally, indicating a requirement for pedagogical measures that disentangle vector analysis into simple processes and promote deeper conceptual understanding within physics classes.

Research on physics education focuses on spatial thinking as a primary component of learning electromagnetism (Hegarty, 2014). Students who lack spatial skills struggle with imagining three-dimensional vector relationships and frequently misuse the right-hand rule or confuse it with the left-hand rule (Ling, et al., 2016). These mistakes can undermine confidence and interfere with learning success, especially among novice students in introductory physics courses. In addition, the body coordination required by the right-hand rule is a disadvantage for kinesthetic or spatially impaired students, further compromising equity in learning (Mayer, 2009). These findings suggest that gesture-free, systematic methods might improve accuracy and engagement, with applications that could extend beyond electromagnetism to STEM fields, such as mechanics, robotics, and computer graphics, where three-dimensional vector analysis is essential. By prioritising mathematical structures over physical movement, instructors can design more accessible and efficient learning environments.

Educational technology has excellent potential to support such alternative pedagogies. Interactive physics simulations, virtual reality spaces, and e-learning modules can model complicated notions like magnetic fields independently of physical motions (Sweller, 2010). For instance, tools like PhET Interactive Simulations enable students to explore vector relationships within dynamic, three-dimensional spaces, and so they are well-positioned to scale up innovative pedagogies in online or blended learning spaces. However, strategies like the right-hand rule are less technology-adaptable and need

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strategies that can be utilized with technology-facilitated teaching to improve spatial awareness and efficiency in problem-solving.

This paper introduces a proposed method, referred to as Farah's Method, and as an alternative to the standard right-hand rule used to determine magnetic force and field directions. Unlike the hand-method widely used in physics textbooks (Serway & Jewett Jr, 2014), Farah's Method involves Cartesian coordinate axis (X, Y, Z) rotations by the smallest angle of rotation, 0° to 180°, in a clockwise or counterclockwise direction. This mathematical method eliminates the necessity for bodily movement, reducing cognitive load and enhancing accuracy in vector analysis. Farah's Method is especially well-suited for implementation in learning technologies, such as virtual labs or simulations, where dynamic visualisation of coordinate rotations can facilitate student learning. By offering a rational, technology-congruent instrument, Farah's Method improves the teaching of electromagnetism and has the potential to generalise to STEM education beyond, breaking down spatial intelligence barriers and improving fair learning.

Glossary

The main terms, abbreviations and symbols used in this paper are listed below:

CW – clockwise rotation
CCW – counterclockwise rotation
RHR – right-hand rule
v – velocity
$\vec{B}$ – magnetic field vector
F – magnetic force
$\vec{v}$ – velocity vector
I – conventional current
$\overrightarrow{dl}$ – infinitesimal length of a conductor carrying an electric current
$\hat{r}$ – unit vector from the wire element to the point where the field is calculated

Farah’s Method

Understanding the orientation of magnetic forces and fields lies at the centre of electromagnetism and is an integral component of physics education. Traditionally, students use the right-hand rule (RHR) to superimpose velocity, magnetic field, and force vectors or to determine magnetic field directions around current-carrying wires (Serway & Jewett Jr, 2014). Yet, the RHR needs accurate hand movement and three-dimensional spatial visualisation, which is difficult for most students, and thus they end up doing it wrong and with the greater cognitive burden (Hegarty, 2014). This paper introduces a proposed method, referred to as Farah’s Method for convenience, which replaces hand movements with mathematical rotations of Cartesian coordinate axes. By offering a systematic, gesture-free approach, Farah's Method enhances precision, reduces intellectual stress, and aligns with educational technologies like interactive simulations, where vector relationships can be visualized dynamically (Mayer, 2009).

Users can determine force direction using Farah's Method because this approach involves step-by-step vector alignment and minimal angular rotation based on Cartesian coordinate system rotations. Users begin by setting the velocity ($\vec{v}$) vector tail to touch the magnetic field ($\vec{B}$) vector tail before marking their positions on the coordinate axes with an additional third free axis. The approach requires users to perform the minimum possible angular rotation $\vec{v}$ toward $\vec{B}$. A clockwise rotational movement of $\vec{v}$ will produce a force $\vec{F}$ that points in the negative direction of the third axis, but counterclockwise rotation produces a force in the positive direction of the third axis.

The advantage of Farah method over the RHR

The RHR needs accurate hand movement and three-dimensional spatial visualisation. Hence, students may end up doing it incorrectly due to misaligning their fingers or failing to map the directions. However, Students who follow the systematic framework of Farah's method no longer require hand movements to determine the magnetic force or field directions as the suggested method is based on the rotation between the axes of the Cartesian coordinates, through the minimal angular path, i.e, the mechanism of locating the magnetic force or magnetic field becomes more comprehensive and more straightforward for all applications.

The application of Farah's method

This section details Farah's Method through three scenarios, comparing its performance to the RHR to demonstrate improved accuracy, conceptual clarity, and ease of use. Diagrams support each scenario to illustrate the method's application in diverse electromagnetic contexts, refer to figures 1 - 10.

The direction of the magnetic forces acting on a moving charge according to Farah's Method

The magnetic force direction can be determined using this method rather than the right-hand rule, as outlined in the steps below:

- Align the vectors $\vec{v}$ and $\vec{B}$ with their tails together, refer to figures 1 and 2.
- Determine on which axis $\vec{v}$ and $\vec{B}$ are located and determine the third free axis.
- Rotate from $\vec{v}$ to $\vec{B}$ through the smaller path of the two possible angles.

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- If the rotation from $\vec{v}$ to $\vec{B}$ is clockwise, then the magnetic force is located on the negative part of the third free axis.
- If the rotation from $\vec{v}$ to $\vec{B}$ is counterclockwise, then the magnetic force is located on the positive part of the third free axis.

As shown in the previous steps, there is no need to use either the right hand or the left hand to determine the direction of the magnetic force.

Figures 1 and 2 show the application of Farah's method to determine the direction of the magnetic force on an electric charge through the rotation from the velocity vector $\vec{v}$ to the magnetic field vector $\vec{B}$.

As shown in Figure 1, the velocity vector $\vec{v}$ is located on the x-axis and the magnetic field vector $\vec{B}$ is on the y-axis, According to Farah's method, the rotation from $\vec{v}$ to $\vec{B}$ through the minimum angular path is counterclockwise (CCW). This means that the magnetic force is located on the positive part of the third free axis, which is z^+ (out of the page).

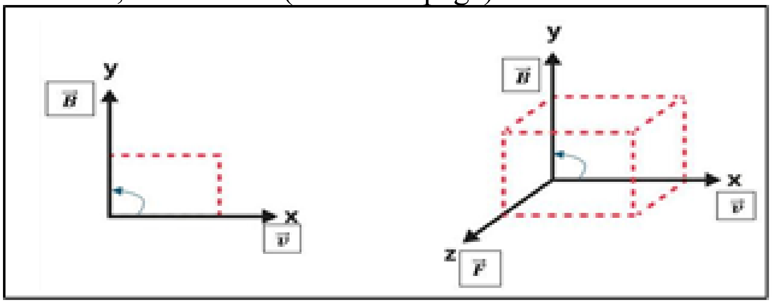

Figure 1. The rotation from $\vec{v}$, on the x axis, to $\vec{B}$, on the y axis, is counterclockwise. Hence, the magnetic force is located on the third free axis, which is the positive z-axis (out of the page).

On the other hand, figure 2 shows that the velocity vector $\vec{v}$ is located on y axis and the magnetic field vector $\vec{B}$ is on the x-axis. The rotation from $\vec{v}$ $\vec{B}$ through the minimum angular path is clockwise (CW). This means that the magnetic force is located on the negative part of the third free axis (z^-, into of the page).

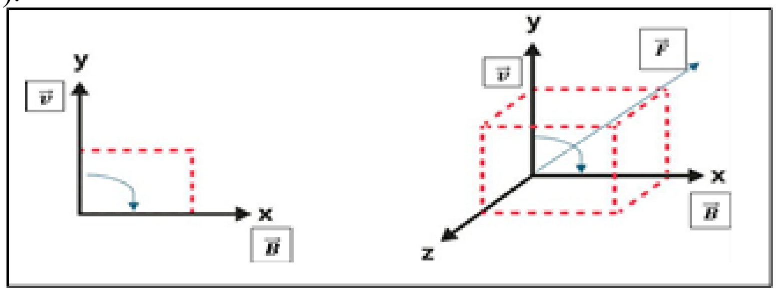

Figure 2. The rotation from$\vec{v}$, on the y axis, to $\vec{B}$, on the x-axis, is clockwise. Hence, the magnetic force is located on the third free axis, which is the negative z-axis (into the page).

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These steps simplify vector analysis, making it ideal for coding into educational software where students can interact with dynamic visualisations.

The magnetic forces acting on a current-carrying conductor according to Farah's Method

To find the direction of the magnetic forces acting on a current-carrying conductor using the method, apply the steps shown in the previous section, replacing the velocity vector $\vec{v}$ by the conventional current (I). Figures 3 and 4 show the application of Farah's method to determine the direction of the magnetic force on a current-carrying conductor through the rotation from the conventional current (I) axis to the magnetic field $\vec{B}$ axis

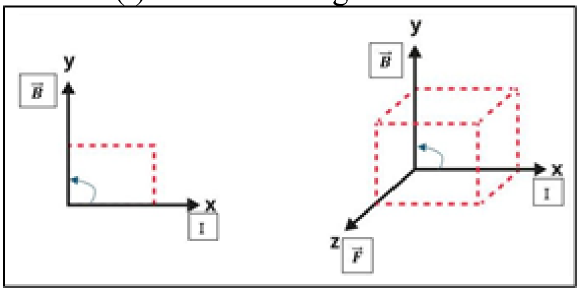

Figure 3. The rotation from I, on the x-axis, to $\vec{B}$, on the y axis. is counterclockwise. Hence, the magnetic force is located on the third free axis, which is the positive z-axis (out of the page).

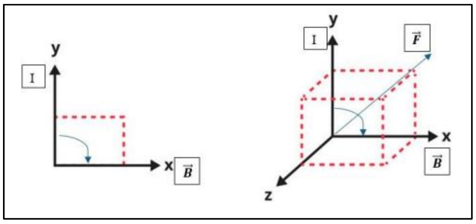

Figure 4. The rotation from I, on the y-axis, to $\vec{B}$, on the x-axis, is clockwise. Hence, the magnetic force is located on the third free axis, which is the negative z-axis (into the page).

This adaptation ensures consistency across applications, supporting virtual lab environments where students can simulate current-induced forces.

The direction of the magnetic field due to a straight current-carrying conductor according to Farah's Method

The magnetic field direction can be determined using Farah's method as follows:

- o Align both vectors $\vec{dl}$ (an infinitesmal length of a conductor carrying an electric current) and $\hat{r}$ (unit vector from the wire element to the point where the field is calculated) with their tails together; refer to figures 5, 6, 7, 8, and 9.

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- Determine on which axis $\overrightarrow{dl}$ and $\hat{r}$ are located and determine the third free axis.
- Rotate from $\overrightarrow{dl}$ to $\hat{r}$ through the smaller path of the two possible angles.
- If the rotation from $\overrightarrow{dl}$ to $\hat{r}$ is clockwise, then the magnetic field $\overrightarrow{B}$ is located on the negative part of the third free axis.
- If the rotation from $\overrightarrow{dl}$ to $\hat{r}$ is counterclockwise, then the magnetic field $\overrightarrow{B}$ is located on the positive part of the third free axis.

Figure 5 below illustrates the magnetic field due to a straight current-carrying conductor. The direction of the current is into the page (Z^-), which generates circular magnetic field lines with a clockwise direction.

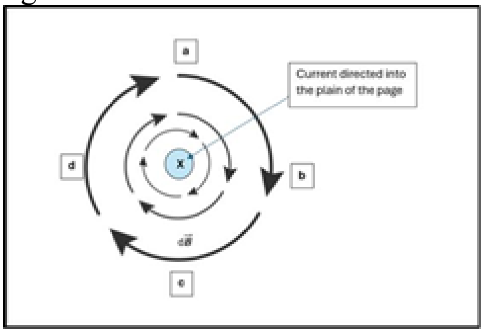

Figure 5. The magnetic field due to a current in a straight wire directed into the page.

Figures 6, 7, 8 and 9 illustrate how Farah's method is employed, as an alternative method to RHR, to determine the direction of the magnetic field at points a, b, c and d, which are shown in Figure 5.

Figure 6 shows the magnetic field at point a; the rotation from the infinitesimal element $\overrightarrow{dl}$, located on the negative z-axis (z^-), towards the position vector $\hat{r}$, located on the positive y-axis (y^+), is counterclockwise. This implies, according to Farah's method, that the magnetic field is located on the positive part of the third free axis, which is the positive x-axis (x^+).

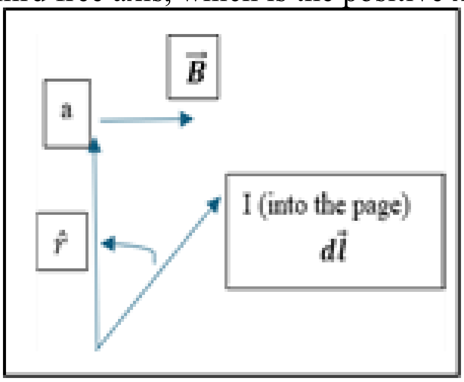

Figure 6. The rotation from $\overrightarrow{dl}$ (z^-) to $\hat{r}$ (y^+) is counterclockwise. Hence, the magnetic field is located on the positive part of the third free axis (x^+).

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Figure 7 shows the magnetic field at point b. The rotation from $\overrightarrow{dl}$, located on the negative z-axis (z^-), towards the position vector $\hat{r}$, located on the positive x-axis (x^+), is clockwise. Consequently, based on Farah's method, the magnetic field is located on the negative part of the third free axis, which is the negative y-axis (y^-).

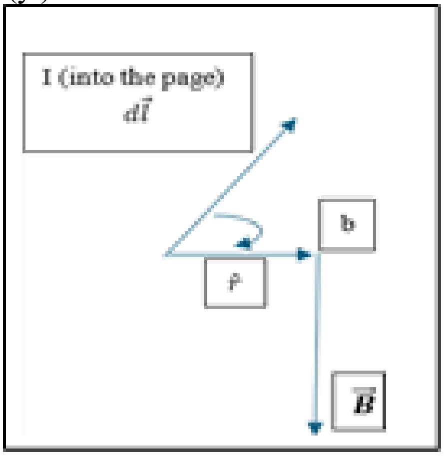

Figure 7. The rotation from $\overrightarrow{dl}$ (z^-) to $\hat{r}$ (x^+) is clockwise, the magnetic field is located on the third free axis, the negative part of it (Y^-).

Regarding the magnetic field at point c (figure 8), at this point, the rotation through the minimal angular path from $\overrightarrow{dl}$, located on the negative z-axis (z^-), towards the $\hat{r}$, located on the negative y-axis (y^-), is clockwise. Subsequently, according to Farah's method, the magnetic field is located on the negative part of the third free axis, which is the negative x-axis (x^-).

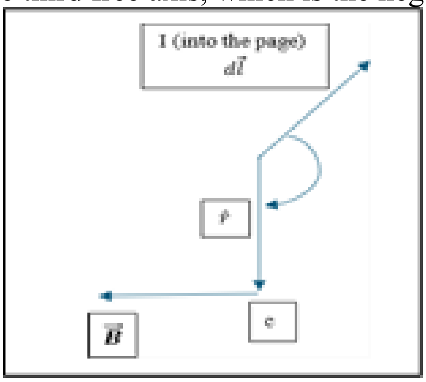

Figure 8. The rotation from $\overrightarrow{dl}$ (z^-) to $\hat{r}$ (y^-) is clockwise, the magnetic field is located on the third free axis, the negative part of it (x^-).

Figure 9_shows the magnetic field at point d. As can be seen in the figure below, the rotation from $\overrightarrow{dl}$, which is located on the negative z-axis (z^-), towards the $\hat{r}$, located on the negative x-axis (x^-), is counterclockwise. This

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implies, based on Farah's method, that the magnetic field is located on the negative part of the third free axis, which is the positive y-axis (y^+).

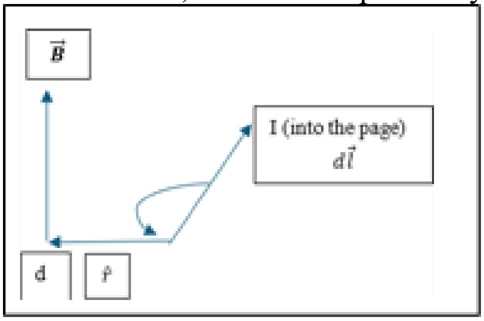

Figure 9. The rotation from $\overrightarrow{dl}$ (z^-) to $\hat{r}$ (x^-) is counterclockwise, the magnetic field is located on the third free axis, the positive part of it (Y^+).

By gathering the directions of the magnetic field at points a, b, c, and d, shown in figures 6, 7, 8 and 9, and considering that the magnetic field direction at any given point in space is the tangent to the field line (Serway & Jewett Jr, 2014), a circular clockwise magnetic field line will be formed, refer to figure 10.

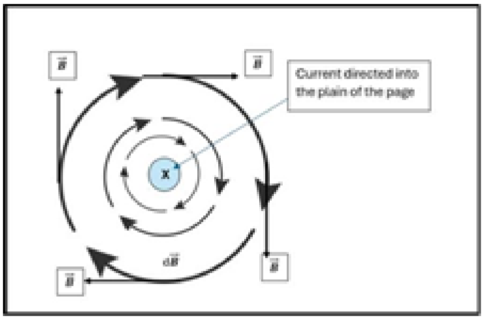

Figure 10. The magnetic field due to a current in a straight wire directed into the page.

This scenario demonstrates the method's versatility, suitable for visualization in 3D simulation tools, enhancing student engagement in physics education.

Methodology

This study evaluates a proposed method, referred to as Farah's Method for convenience, as an alternative to the traditional right-hand rule (RHR) for determining magnetic field and force directions in electromagnetism. By replacing hand gestures, spatial visualisation-based, with Cartesian coordinate rotations, axis rotation-based, Farah's Method aims to enhance student understanding, particularly for those challenged by the RHR's three-dimensional visualisation and hand-positioning requirements (Hegarty, 2014). The effectiveness of the method is assessed in this study using a quasi-

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experimental design through comparison of learning outcomes among students who use Farah's Method and those who use the RHR. The methodology entails participant recruitment, instructional interventions, assessment design, and data analysis in order to achieve a robust test of this method's impact on physics teaching. This is on par with technology-supported learning spaces, where computer capabilities such as virtual simulations can facilitate instruction in vector analysis (Mayer, 2009).

Participant Selection and Sampling

The study involved 60 secondary school students enrolled in an IGCSE introductory electromagnetism course. Students were assigned randomly to two groups of 30 students each: a control group taught using the RHR and an experimental group taught using Farah's Method. Random assignment controlled for biases in relation to previous knowledge or cognitive ability with similar baseline characteristics. A power analysis was used to estimate the sample size with a desired effect size of Cohen's $d > 0.8$ to detect significant differences in learning gain (Cohen, 1988). The rigorous selection process enhances the validity and generalizability of the study to similar educational contexts, for example, technology-enabled STEM programs.

Instructional Intervention

Both classes had access to identical instructional content, including lectures, problem sets, and guided practice in magnetic force and fields, instructed over two weeks by a single instructor. The only variation was how vector directions were chosen. The control group used the RHR, utilizing hand motions to align velocity, magnetic field, and force vectors, as found in standard physics textbooks (Serway & Jewett Jr, 2014). The experimental group, however, was taught Farah's Method, which involves minimal-angle clockwise or counterclockwise rotation of Cartesian coordinate axes to define vector directions without actual motion.

Instructional materials were consistent across groups, ensuring equal exposure to practice problems. The use of a single instructor minimized variability in teaching style, isolating the effect of the instructional method. Farah’s Method’s structured approach is compatible with digital platforms, such as interactive physics simulations, where coordinate rotations can be visualised to enhance student engagement (Sweller, 2010). This intervention design supports the study’s aim to evaluate a scalable, technology-compatible pedagogy for STEM education.

Assessment Design

To evaluate Farah’s Method, assessments measured conceptual understanding, problem-solving accuracy, and efficiency. All students

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completed a 20-item multiple-choice pre-test to assess their baseline knowledge of electromagnetism. The test, validated by subject-matter experts, demonstrated strong internal consistency (Cronbach's $\alpha = 0.82$). For your reference, a sample of a few pre-test questions is shown below in Figure 11.

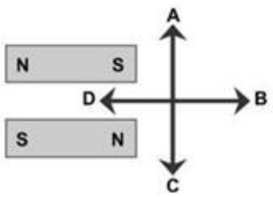
A post-test mirrored the pre-test's structure but included new questions in order to evaluate the conceptual development after the two-week intervention (see Figure 12).

2. The magnetic field unlike the electric field is continuous.
   a. true
   b. false

3. If the north poles of two bar magnets are brought close to each other, the magnets will:
   a. attract.
   b. repel.

4. If the south pole of one bar magnet is brought near the north pole of a second bar magnet, the two magnets will:
   a. attract.
   b. repel.

5. The figure below shows 2 bar magnets of the same size and the same strength. Which of the arrows labelled A to D correctly represents the direction of the magnetic field at a point located at the common origin of the arrows? (That point is at an equal distance from the two magnets.)



   a. A
   b. B
   c. C
   d. D

Figure 11. Sample of the pre-test questions

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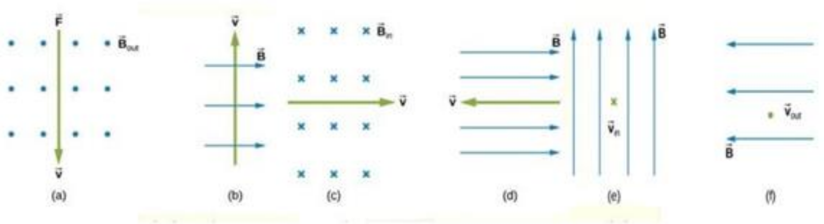
7. Determine the direction of the magnetic force on a **positive** charge that moves as shown in each of the six cases?



8. The direction of the force on a current-carrying wire in a magnetic field is described by which of the following?

   a. parallel to the current only
   b. parallel to the magnetic field only
   c. perpendicular to the current only
   d. perpendicular to the magnetic field only
   e. perpendicular to both the current and the magnetic field

9. The force on a current-carrying wire in a magnetic field is the strongest when

   a. the current is parallel to the field lines.
   b. the current is at a 30° angle with respect to the field lines.
   c. the current is at a 45° angle with respect to the field lines.
   d. the current is at a 60° angle with respect to the field lines.
   e. the current is perpendicular to the field lines.

Figure 12. Sample of post-test conceptual questions that all the students had to complete after the two-week intervention.

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4. A straight wire 20 cm long, carrying a current of 4 A, is in a uniform magnetic field of 0.6 T. What is the force on the wire when it is at an angle of 30° with respect to the field?
    a. 0.2N
    b. 0.3N
    c. 0.4N
    d. 0.5N
    e. 0.6N

5. An alpha particle is moving at a speed of 5×10^5 m/s in a direction perpendicular to a uniform magnetic field of strength 4×10^{-2} T. The charge on an alpha particle is 3.2×10^{-19} C and its mass is 6.6×10^{-27} kg.

    a. As the alpha particle moves, its velocity is directed

    ____

    b. The magnitude of the force on the alpha particle is

    ____

6. A long, straight wire conductor carries a 2.0A current. What is the distance from the axis of the conductor that will make the resultant magnetic field have a magnitude of 0.3×10^{-4} T?

Figure 13. Sample of problem-solving activities that were used to determine both the accuracy and the efficiency.

Additionally, students completed 10 problem-solving tasks requiring magnetic field and force calculations. Figure 13 above, shows an extract of the problem-solving assessment, which illustrates both multiple-choice and free-response problems that students had to solve. Accuracy was measured as the percentage of correct solutions, while efficiency was assessed by recording the time taken per task. These assessments were designed to be adaptable to digital platforms, such as online quiz systems or virtual labs, enhancing their relevance to technology-driven education (Mayer, 2009). The combination of multiple-choice and problem-solving tasks provided a comprehensive evaluation of learning outcomes.

Data Analysis and Justifications

Mean scores and standard deviations were calculated for pre-test, post-test, problem-solving accuracy, and completion times. Paired t-tests compared pre-test and post-test scores between groups to assess instruction effectiveness. Independent t-tests compared post-test scores and problem-solving accuracy in the RHR group versus the Farah's Method group to test the hypothesis that Farah's Method yields superior results. Completion times

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were similarly compared to assess efficiency. These statistical tests, while controlling for differences in individual performance, provided a rigorous comparison (Cohen, 1988). Statistical software was utilized to examine data according to technology-supported research protocols in educational research.

Analysis

This study assessed the efficacy of the proposed technique, simply referred to as Farah's Method, as a replacement for the traditional RHR in determining magnetic field and force directions in electromagnetism. By employing Cartesian coordinate rotations instead of hand gestures, Farah's Method aims to improve student understanding, problem-solving accuracy, and efficiency and reduce cognitive load (Hegarty, 2014). The research combines quantitative metrics (pre/post-test performance, problem-solving accuracy, efficiency) with qualitative metrics (subjective cognitive load) to evaluate the effect of the method. Results were calculated with statistical software, adhering to technology-aided best practices, and have instructional implications for digital learning systems where data visualisation and interactive quizzes can more effectively instruct STEM subjects (Mayer, 2009).

Comparative Analysis of Learning Gains

To measure learning gains quantitatively, students were assessed using pre-test and post-test scores. Descriptive statistics in Table 1 show a significant increase in students' understanding after instruction in both methods.

Table 1. Descriptive Statistics for Pre-Test and Post-Test Scores

Group	Pre-Test Mean (%)	Pre-Test SD	Post-Test Mean (%)	Post-Test SD
Right-Hand Rule	42.03	2.48	61.27	3.72
Farah’s Method	41.57	2.27	80.47	3.98

The pre-test mean scores of both groups were similar (42.03% for RHR and 41.57% for Farah's Method, refer to Table 2), indicating that students had equal prior knowledge. However, with instructional intervention, Farah's Method performed better, with an average post-test score of 80.47%, while that of the RHR group stood at 61.27%. A paired t-test was employed to determine the statistical significance of the gains in learning between each of the groups.

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Table 2. Paired t-Test for Pre-Test and Post-Test Scores

Group	Mean Difference (%)	t-value	p-value (α=0.05)	Effect Size (Cohen's d)
Right-Hand Rule	19.24	14.27	<0.001	2.01
Farah's Method	38.9	23.89	<0.001	3.42

Both conditions significantly improved ($p < 0.001$), with Farah's Method being more effective ($d = 3.42$) than RHR ($d = 2.01$), reflecting greater conceptual knowledge and learning (Cohen, 1988). The findings imply the usability of the method by integrating it into online assessment platforms, where immediate feedback could be provided to enhance learning performance.

Post-Test Comparison Between Groups

To compare the post-test performance of both groups, an independent t-test was conducted (refer to Table 3).

Table 3. Independent t-Test for Post-Test Scores

Comparison	Mean Difference (%)	t-value	p-value (α=0.05)
Farah's vs. RHR	19.2	18.72	<0.001

The significant mean difference (19.20%, $p < 0.001$) once again confirms that Farah's Method outshone RHR, demonstrating that Cartesian rotations support a more profound understanding than hand gestures. This advantage supports the method's flexibility to suit virtual learning environments, in which visualisations using coordinates can be implemented.

Conceptual Understanding and Problem-Solving Accuracy

The assessment of conceptual understanding relied on problem-solving accuracy, which evaluated students ability to identify proper forces and field directions (refer to Table 4).

Table 4. Problem-Solving Accuracy Comparison

Group	Mean Accuracy (%)	SD
Right-Hand Rule	66.87	3.21
Farah's Method	87.63	2.74

The results demonstrated statistical significance through an independent t-test analysing accuracy levels (refer to table 5):

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Table 5. Independent t-Test for Problem-Solving Accuracy

Comparison	Mean Difference (%)	t-value	p-value (α=0.05)
Farah's vs. RHR	20.76	22.84	<0.001

Students who applied Farah's Method achieved 87.63% mean accuracy and outperformed RHR users, who reached 66.87%. The statistical significance of this improvement becomes evident through a high t-value (22.84) together with a p-value below 0.001. The research demonstrates how removing hand movements from the process leads to better accuracy performance during three-dimensional force and field problem-solving. This precision is valuable for digital simulations, where accurate vector modelling enhances student engagement (Sweller, 2010).

Efficiency: Time Taken per Question

The evaluation of method efficiency measured how much time students needed to answer each question with the two different procedures (see Table 6).

Table 6. Average Time Taken per Question

Group	Mean Time (sec)	SD
Right-Hand Rule	53.12	3.72
Farah's Method	35.87	2.83

Table 7. Independent t-Test for Time Efficiency

Comparison	Mean Difference (sec)	t-value	p-value (α=0.05)
Farah's vs. RHR	17.25	19.63	<0.001

Students who used Farah's Method needed 17.25 seconds less to solve problems, which researchers confirmed as statistically significant ($p < 0.001$). Students needed fewer mental resources because of this, which enabled them to answer questions at a faster pace (refer to table 7). It indicates reduced cognitive effort and faster processing, ideal for time-sensitive digital assessments.

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Cognitive Load and Student Perception

A Likert-scale questionnaire accompanied the cognitive load assessment through which students graded the usage difficulty of each method (1–5).

Table 8. Perceived Cognitive Load (Mean Ratings)

Method	Spatial Complexity	Mental Effort	Ease of Use	Overall Rating
Right-Hand Rule	4.23	4.11	2.76	3.7
Farah's Method	2.14	2.27	4.52	4.31

As shown in Table 8, students found Farah's Method more convenient to apply based on their average scores of 4.31 compared to RHR at 3.70. Students invested less effort in acquiring orientations (2.27 vs. 4.11) compared to Cartesian coordinate rotation using other methods (2.14 vs. 4.23). These results affirm the suitability of the method for technologically rich environments, where simple interfaces reduce cognitive load (Sweller, 2010).

Discussion of findings

In this study, this novel method is demonstrated to enrich the traditional right-hand rule (RHR) employed to teach directions of magnetic field and force in electromagnetism by replacing hand movements with Cartesian coordinate rotations. The method improves learning, accuracy and problem-solving speed, as well as minimises cognitive load (Hegarty, 2014). These results have instructional implications for physics instruction and adhere to technology-enhanced learning since computational software, such as interactive simulations, can reproduce coordinate rotations to aid student learning (Mayer, 2009). The organised structure of the method also has potential use within other STEM courses, including mechanics and computer graphics, where three-dimensional vector analysis is essential.

Enhanced Learning Outcomes

Post-test results showed substantial gains in learning by the Farah's Method group, 80.47% mean versus 61.27% for the RHR group, a 19.20% difference ($p < 0.001$). Pre-test results were comparable (Farah's Method: 41.57%, RHR: 42.03%), validating equivalent baseline knowledge. The larger effect size for Farah's Method (Cohen's $d = 3.42$ vs. RHR: $d = 2.01$) demonstrates more effective knowledge recall and application (Cohen, 1988). This improvement comes from the method's dependence on mathematical transformations rather than hand movement, which makes cognitive processes simpler. Unlike the RHR, with its students' coordination of hand movement and visualisation of three-dimensional relationships, Farah's Method uses

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rotation of coordinate axes in a clockwise or counterclockwise direction, which reduces spatial-visualisation errors. These advantages are ideally suited for computer learning environments like PhET simulations, in which dynamic visualisations can be used to aid in conceptual understanding (Sweller, 2010).

Improved Problem-Solving Accuracy and Efficiency

Farah's Method led to a significantly higher accuracy in problems solved, with students attaining a mean accuracy of 87.63% compared to 66.87% for RHR users, a difference of 20.76% ($p < 0.001$). The accuracy is attributed to the systematic nature of the method, which avoids the hand-positioning errors prevalent in the RHR. Furthermore, students who employed Farah's Method solved problems more quickly, averaging 35.87 seconds per problem versus 53.12 for RHR users, a reduction of 17.25 seconds ($p < 0.001$). RHR's reliance on iterative hand modification increases cognitive duration and effort, while Farah's Method's coordinates-based thinking maximises decision-making. This kind of efficiency can work in favour of technology-enabled assessment, in which time-dependent activities can be incorporated into online modules or virtual labs and lead to increased student engagement in STEM courses.

Reduced Cognitive Load

Cognitive load measures confirmed that Farah's Method is less cognitively demanding. Students scored their spatial complexity (2.14 vs. 4.23), mental effort (2.27 vs. 4.11), and general difficulty lower than the RHR, but with higher ease of use (4.52 vs. 2.76). The visual and kinesthetic requirements of the RHR impose heavy psychological burdens, particularly for learners with spatial thinking difficulties (Hegarty, 2014). On the other hand, the mathematical form of Farah's Method decreases cognitive workload, allowing the method to be applied by different learners. This aligns with cognitive load theory and enables its use in digital interfaces, where the reduction of visualizations decreases mental strain (Sweller, 2010).

Educational Implications

Farah's Method is a pioneering pedagogy for teaching physics beyond the limits of the RHR for spatial or kinesthetic students. Its gesture-free, technology-compatible design suits contemporary pedagogical aspirations for conceptual understanding rather than memorisation. By leveraging tools such as virtual reality or simulation software, instructors can adopt the method in online, blended, or classroom learning environments, improving accessibility and equity in STEM subject learning. Its application is found in all areas that require vector analysis, e.g., robotics and engineering, hence expanding its use in academia.

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Limitations and Future Research

Although it has its merits, the research has its limitations. The sample was restricted to IGCSE-course high school students, with possible limitations in generalizability to advanced physics or engineering applications. Long-term retention and applicability to complicated situations (e.g., non-orthogonal vectors) were not measured. Certain students with existing knowledge on the RHR might be resistant to changing to another approach, which indicates a gradual introduction as a requirement. Long-term retention, application on upper-level courses, and increased incorporation of technology like augmented reality, where 3D visualisations can even decrease cognitive load even more, are some directions to be explored in future research. Research with more heterogeneous populations, such as younger students or non-STEM majors, might also make the approach even more generalisable.

A significant limitation encountered in this study is the scarcity of reliable resources addressing alternative approaches to the right-hand and left-hand rules, which remain dominant in mainstream physics textbooks. The method proposed in this research represents a novel, hands-free approach for determining the direction of the magnetic field and force. Based on the data analysis, it can be argued that this method has the potential to serve as an effective substitute for the conventional right-hand/left-hand rules.

Conclusions

The research proposed a new approach, referred to as Farah's Method, as an alternative to the conventional right-hand rule (RHR) for determining directions of magnetic fields and forces in electromagnetism. While RHR depends on hand movements and intuition about three-dimensional space, Farah's Method utilises deterministic Cartesian coordinate axes rotation to enable vector analysis (Hegarty, 2014). The results show that this gesture-free method considerably improves student comprehension, accuracy in problem-solving, and speed and lowers cognitive load when compared to the RHR. Due to its logical and easy-to-implement methodology, Farah's Method abolishes memorized physical gestures, making it a more efficient and accessible tool for physics instruction.

The quasi-experiment with 60 high school participants showed that Farah's Method resulted in improved learning, with average post-test scores of 80.47% as opposed to 61.27% in the RHR group ($p < 0.001$). Accuracy in problem-solving was higher (87.63% vs. 66.87%), and it took students less time to solve problems (35.87 seconds vs. 53.12 seconds), while perceived cognitive load was lower (overall rating: 4.31 vs. 3.70). These results show the effectiveness of the method in automating cognitive processes and increasing conceptual clarity, particularly for spatial reason or kinesthetic challenges. (Sweller, 2010). Farah's Method not only outperforms traditional

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approaches but also supplements technology-mediated environments, such as PhET Interactive Simulations or virtual worlds, where rotation of coordinates can be viewed live to engage the students (Mayer, 2009).

Farah's Method has far-reaching implications for the teaching of physics today, providing a technology-sensitive and scalable pedagogy that encourages conceptual understanding over rote memorisation. Its applications are not limited to electromagnetism alone but can be extended to other STEM disciplines such as mechanics, engineering, and computer graphics, where three-dimensional vector calculus is the governing paradigm. By its integration with digital platforms, including augmented reality interfaces or computer-based testing systems, the approach can reach its greatest access and equity in STEM learning, meeting diverse needs of learners within classroom and online environments. Farah's Method, with its integration into educational technology, represents a revolutionary methodology for rethinking STEM teaching.

Although it has some benefits, the study's scope was limited to high school students who were enrolled in an IGCSE curriculum, and applicability or retention in more advanced physics subjects (e.g., non-orthogonal vectors) is left to be determined. Future studies should test the effectiveness of the approach with higher-level physics and engineering courses as well as with diverse student populations, such as younger students or non-STEM majors. Examining integration with cutting-edge technologies, such as augmented reality or adaptive learning software, could further enhance its teaching potential. Moreover, research needs to test whether exposure to the RHR discourages adoption of Farah's Method and whether and how phased implementation strategies can overcome resistance.

In conclusion, Farah's Method is an innovative approach to electromagnetism education that provides a precise, efficient, and accessible solution to the RHR. Its mathematical structure and flexibility to utilize digital learning media make it a strong prospect to be universally implemented in physics classes. The science community is invited to further explore its effectiveness through various learning contexts and integrate it into technology-aided curricula to maximize its impact on STEM learning achievement.

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