

Student difficulties and alternative conceptions in learning particle motion in force fields

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Understanding particle motion in force fields (PMFF), which encompasses the nature of forces and the relationship between force and motion, is fundamental to mastering mechanics and electromagnetism. Effectively solving PMFF-related problems requires advanced reasoning skills and the ability to apply knowledge across diverse contexts. Despite evidence that students often encounter significant challenges with these concepts, comprehensive assessment tools to reliably evaluate their understanding remain limited. In high school and introductory college physics courses, the most commonly studied force fields include those generated by a point mass or a point charge, as well as uniform gravitational, electric, and magnetic fields. The basic types of motion observed in these fields include uniform linear motion, uniformly accelerated rectilinear motion, uniformly accelerated curvilinear motion, and uniform circular motion. This study developed a nine-item multiple-choice test designed to assess students' understanding of PMFF concepts. Data were collected from 34 college physics majors using test scores, interviews, and eye-tracking technology. The analysis revealed several alternative conceptions that varied depending on the specific force field context. Students performed relatively well in uniform force field scenarios but faced significant difficulties with fields generated by a point mass or a point charge, as well as uniform magnetic fields. In fields of a point mass or point charge, common misconceptions centered on uniformly accelerated motion. In the uniform magnetic field context, students often struggled to differentiate between uniform linear motion and uniformly accelerated curvilinear motion. Eye-tracking data provided additional insights, revealing attention patterns that corroborated the observed difficulties. These findings highlight critical areas where students face challenges in understanding PMFF. The results can guide future research efforts to develop targeted educational interventions aimed at addressing these specific learning difficulties, ultimately improving student comprehension of PMFF concepts.

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I. INTRODUCTION

Particle motion in force fields (PMFF) is a foundational concept in mechanics and electromagnetism, requiring students to develop a deep understanding of the relationship between force and motion in complex contexts. Numerous studies have investigated students' conceptual

understanding of force and motion across varying levels of complexity [1–7], consistently finding that students often struggle with basic ideas, such as the belief that an object in motion must have a force acting on it. These incorrect or incomplete understandings are commonly referred to as misconceptions, preconceptions, initial conceptions, alternative ideas, and other similar terms [8–11]. For the purposes of this paper, the terms “alternative conceptions” and “learning difficulties” will be used as the broad descriptors encompassing the various types of nonscientific understandings commonly observed among students.

In physics, fields are used to represent long-range, force-based interactions between objects [12]. Developing a correct understanding of the force exerted on a particle in a force field—and how that force influences the particle's motion—is a critical step in learning advanced physics

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concepts. Existing research indicates that students often encounter significant difficulties when solving problems related to particle motion in specific force fields [13,14]. However, there is a noticeable gap in the physics education research literature regarding studies that specifically focus on student learning of particle motion in force fields (PMFF).

To address this gap in the literature, this study develops a PMFF test that incorporates varied force fields to explore students' alternative conceptions about PMFF. To gain a deeper insight into students' reasoning processes in solving physics problems, eye-tracking technology has been increasingly used in recent studies [15–20]. Therefore, this study integrates the eye-tracking technology with quantitative assessment data and qualitative interviews in order to thoroughly examine students' alternative conceptions of PMFF.

II. LITERATURE REVIEW

A. Physical properties and assessment of particle motion in force fields

The PMFF constitutes the core elements of fundamental physics, requiring students to understand both force-motion relationships and the specific characteristics of forces acting on particles within force fields. This comprehensive understanding is essential for learning more advanced topics in physics.

Force and motion have long been a central focus in physics education research (PER). Identified as one of the four disciplinary core ideas in physical science by the Next Generation Science Standards [21], this concept demands students to apply Newton's laws of motion to explain force-motion relationships and understand fundamental motions influenced by common forces, including gravity, electrostatic field force, and magnetic field force. Nevertheless, students frequently hold strong alternative views about these concepts, which persist even after instruction and significantly impact their problem-solving and future learning [22].

To address these alternative conceptions, numerous studies have explored students' understanding of force and motion, resulting in the development of various assessment tools [13,14,23–27]. These instruments primarily examine the relationship between force and four types of motion, including uniform linear motion, uniformly accelerated rectilinear motion, uniformly accelerated curvilinear motion, and uniform circular motion, as summarized in Table I. Correctly determining a particle's motion requires evaluating both the direction of the net force (F_{net}) relative to its trajectory and the magnitude of F_{net} . For uniform linear motion, it is sufficient to confirm whether the magnitude of F_{net} is zero. While existing tools primarily focus on analyzing the relationship between the direction of

TABLE I. The four basic motions and their characteristic of net force (F_{net}) on the particles.

Motion	Characteristic of F_{net}
Uniform linear motion	F_{net} is zero.
Uniformly accelerated rectilinear motion	The magnitude of F_{net} remains constant, and so does its direction, which is parallel to the velocity.
Uniformly accelerated curvilinear motion	The magnitude of F_{net} remains constant, and so does its direction, which is not parallel to the velocity.
Uniform circular motion	The magnitude of F_{net} remains constant, but the direction changes, which always points toward the center of the circle.

F_{net} acting on a particle and its trajectory [23–25], a comprehensive evaluation of force magnitude across all motion types remains limited. Although the Mechanics Baseline Test (MBT) and the Force and Motion Conceptual Evaluation (FMCE) assess the magnitude of F_{net} , they primarily address uniformly accelerated rectilinear motion. Notably absent is the evaluation of the magnitude of F_{net} in both uniformly accelerated curvilinear motion and uniform circular motion, despite their critical importance in learning advanced physics topics [2]. In addition, most of the existing assessment tools were developed in simple mechanics contexts, with contact forces being the main scenario. Evaluation of students' understanding of applied forces in simple to complex force fields is largely missing in the existing assessments.

In introductory physics, common force fields include the gravitational field of a point mass, uniform gravitational field, the electrostatic field of a point charge, uniform electric field, and uniform magnetic field [28]. Based on the feature of magnitude and direction of the forces acting on a particle within these force fields, three general computational forms can be categorized: force field of a point mass or charge, uniform electric or gravitational force field, and uniform magnetic field.

First, the force field of a point mass or charge includes the gravitational field of a mass point and the electrostatic field of a point charge. Within the gravitational field g generated by a mass point M , the force experienced by another mass point m is given by the universal law of gravitation, $\vec{F}_g = -\frac{GMm}{r^2}\hat{r}$, where G is the gravitational constant and r is the distance from m to M . Similarly, in the electric field E generated by a point charge Q , a second point charge q experiences a force determined by Coulomb's law $\vec{F}_e = \frac{kQq}{r^2}\hat{r}$, where k is a constant and r is the distance from q to Q . Since the magnitudes of these forces follow the inverse square of r and their directions are radial, they present similar computational properties.

Second, the uniform force fields include a uniform gravitational field and a uniform electric field. The gravitational field near the surface of the Earth is approximated with a uniform gravitational field, where g is constant. The force experienced by a mass point m is determined by $\vec{F}_g = m\vec{g}$. A uniform electric field refers to an electrostatic field in which the electric field strength E is the same in magnitude and direction at all points. The force on a charged particle q in this field is given by $\vec{F}_e = q\vec{E}$. Given that both the magnitude and direction of these forces remain constant in the defined spaces, they both present similar computational properties.

Third, in a uniform magnetic field, the force (as a vector) experienced by a point charge q is described by the Lorentz force $\vec{F} = q\vec{v} \times \vec{B}$. Operation-wise, the magnitude of the force can be calculated as $F = qvB \sin \theta$, where θ is the angle between the direction of v and B , and only the component of the velocity perpendicular to B affects the magnitude of F . The direction of the force is determined by the right-hand rule.

Existing research on the assessment of PMFF is limited. Some studies have examined the forces acting on the particle within a force field, but without addressing the particle motions [14,29]. Several instruments have investigated particle motion within certain specific force fields, with a primary emphasis on linear motion. For instance, the Conceptual Survey of Electricity and Magnetism (CSEM) tested uniformly accelerated rectilinear motion in a uniform electric field [29]. The Brief Electricity and Magnetism Assessment (BEMA) examined uniform linear motion in a composite field of uniform electric and magnetic fields [14]. Nonetheless, questions presented in these assessment tools are limited to simple and very specific contexts, making it difficult to fully gauge students' understanding of PMFF.

To address the gap in the literature, this study aims to identify the challenges students encounter in solving PMFF problems across a broad range of contexts and complexity. To assess students' problem-solving abilities across these contexts, the design incorporates both single fields and composite fields. Since the force field of a point mass or charge is inversely proportional to r^2 , their superposition with other fields leads to complex motions beyond the common types previously discussed. Consequently, in this study, the question designs on composite fields only include uniform force fields and uniform magnetic fields.

B. Eye tracking in PER

Eye-tracking technology has emerged as a powerful tool in education research, providing an objective method to investigate how students engage with visual information. It is widely applied in various domains, including reading [30], information processing [31], multimedia learning

[32–34], problem solving [35,36], and other research areas. According to the eye-mind hypothesis, there is a strong correlation between eye movement and attention [37]. Moreover, eye movements can reveal students' cognitive processes, offering detailed insights into where and how students allocate cognitive resources during learning tasks [31,38]. Recently, there has been a growing trend in PER to complement eye-tracking data with qualitative methods, such as interviews [15,39]. This approach enriches the analysis by providing additional information about students' learning behaviors and performances that eye-tracking alone cannot capture. While eye-tracking data typically reveals where students look and how long they focus on specific areas, it does not inherently explain the reasoning behind these visual behaviors. By integrating interviews, researchers can probe students' thought processes more directly, linking specific eye movement patterns with the underlying cognitive strategies and alternative conceptions [15,16,40–43]. Therefore, in this study, we triangulate three forms of measurement, including eye-tracking, interviews, and test scores, to complement each other and identify students' learning difficulties related to PMFF.

Current eye-tracking research in PER has primarily examined variations in eye movements among students of different performance levels in response to various stimuli [15]. For example, Langendorf *et al.* employed eye-tracking technology to analyze students' comprehension of the Hertzprung-Russell diagram (HRD). They divided the diagram into specific areas of interest (AOIs) and compared visit durations and counts in these AOIs between the HRD and the context-free diagram (CFD), confirming that students encountered greater difficulties with the HRD [16]. Similarly, Susac *et al.* explored students' challenges in understanding graph slope and area under a graph across varying contexts. They categorized the items into distinct AOIs (question, graph, and multiple choice) and examined fixation times for the entire item as well as individual AOIs, demonstrating students' learning difficulties with graph slope and area [44]. Additionally, they measured the eye movements of high school students when identifying diffraction patterns generated by monochromatic light through double slits, single slits, diffraction grating, and white light on diffraction grating. By comparing dwell time, number of fixations, fixation duration, and number of revisits to diverse AOIs (text of question and diverse options), they investigated students' difficulties in recognizing single-slit diffraction and double-slit interference patterns [45]. These studies suggest that variations in eye movement metrics, on both an entire item and its specific AOIs, can provide useful evidence for inferences on students' learning difficulties.

C. Research questions

This study addresses the primary research question: What types of learning difficulties can be identified when

students solve problems about PMFF? To answer this, we examined the effects of various factors on student performance, drawing on test scores, interview data, and eye-tracking analysis. Specifically, we investigated (a) the impact of different force field contexts, namely, the field of a point mass or charge, the uniform force field, and the uniform magnetic field; and (b) how students' understanding of key concepts, such as force fields, uniform linear motion, uniformly accelerated rectilinear motion, uniformly accelerated curvilinear motion, and uniform circular motion, influenced their overall problem-solving performances.

III. METHOD

A. Participants

Existing research has shown that even high-achieving students often remain committed to nonscientific alternative conceptions or misconceptions about Newtonian mechanics [5,6,46–50]. In a previous study [51], we observed that students from an advanced class at an elite high school demonstrated misunderstandings related to PMFF. Consequently, we extended this research to college students majoring in physics to further investigate the challenges they continue to face in this area.

The study recruited 38 college students majoring in physics from a teacher education university in China, all of whom participated voluntarily. Each student had completed college-level mechanics and electromagnetism courses, leading us to anticipate minimal difficulty with PMFF, as these concepts are typically covered in Chinese high school physics. Due to technical issues with the eye-tracking equipment or missing gaze data, some participants' data were excluded, resulting in a final dataset of 34 students (17 females and 17 males). All participants had normal or corrected-to-normal vision.

B. Study design and procedure

The study was carried out in a specialized eye-tracking laboratory. Initially, demographic data (name, gender, age, and grade) were collected from each participant. Participants were then seated in front of the eye-tracking device while a researcher introduced the whole laboratory environment and experimental procedures. To ensure measurement accuracy, participants were instructed to keep their heads and bodies as still as possible during the experiment, precluding the use of paper and pencil. Prior to data collection, a nine-point calibration procedure was performed to validate the eye-tracking system's accuracy.

Participants completed a practice experiment to familiarize themselves with the testing environment, using a keyboard for navigation and a mouse for answer selection. The computer recorded their answers, which could be exported after the experiment. Once participants were comfortable with the setup, they proceeded to the formal experiment. Questions were presented individually without

time constraints, and participants completed each item independently, with no option to revisit previous questions once answered.

Following the eye-tracking session, semistructured interviews were conducted to elicit participants' thought processes during the test. Participants were provided with paper materials to assist in their retrospective reporting. The following guiding questions were used to encourage participants to reconstruct their reasoning as accurately as possible and to explain any errors identified with their initial reasoning: How did you analyze the item, and how did you arrive at your answers? Please describe the thought process you followed. When responses were unclear, the researcher asked follow-up questions to ensure clarity. For example: "Can you draw the forces acting on the particle?" or "Could you explain again how you arrived at this choice?" All interviews were audio-recorded for later analysis.

C. Design of the PMFF test

The test comprises nine multiple-choice, multiple-response questions designed to evaluate particle motion across three types of force fields, summarized in Table II. For each question, students are asked to determine the motion of a particle within a specified force field context from four provided options. For single-field contexts, students must analyze the forces acting on the particle and the relationship between force and motion. In the case of composite fields contexts, students are additionally required to apply the superposition principle to combine the forces from multiple fields.

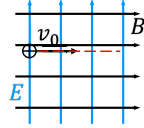
An example question is presented in Fig. 1. In this question, students are asked to identify the possible motions a particle can exhibit in a composite field where uniform gravitational, electrical, and magnetic fields

TABLE II. A description of the PMFF test's contexts of force field.

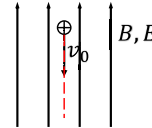
Types of force field	Item	Item context of force field
Field of a point mass or charge	Q1	Gravitational field of a mass point
	Q3	Electrostatic field of a point charge
Uniform force field	Q2	Uniform gravitational field
	Q4	Uniform electrical field
	Q6	Uniform gravitational field and uniform electrical field
Uniform magnetic field	Q5	Uniform magnetic field
	Q7	Uniform electrical field and uniform magnetic field
	Q8	Uniform gravitational field and uniform magnetic field
	Q9	Uniform gravitational field, uniform electrical field, and uniform magnetic field

9. In a region where only a uniform gravitational field (directed vertically downward, not depicted in the four options), a uniform electric field, and a uniform magnetic field exist, a positively charged mass point enters this area with a velocity v_0 . Which of the following statements about the mass point's motion may be correct? In option B, B and E are in the same direction.

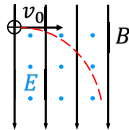
A. The particle may undergo uniform linear motion.



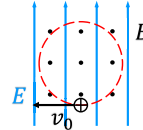
B. The particle may undergo uniformly accelerated rectilinear motion.



C. The particle may undergo uniformly accelerated curvilinear motion.



D. The particle may undergo uniform circular motion.



(The red line indicates the particle's trajectory; The blue indicates E ; The black indicates B .)

FIG. 1. Q9 of the PMFF test. The question text outlines the force field context, with each of the four options corresponding to a distinct type of motion. Each option provides a scenario detailing the particle's velocity and possible trajectory.

coexist. Consistent with the conventions of Chinese physics textbooks, the gravitational field of a point mass and the uniform gravitational field are not represented using field lines. In contrast, the electrostatic field of a point charge, the uniform electric field, and the uniform magnetic field are depicted with their respective field lines, as illustrated in Fig. 1. This distinction aligns with traditional teaching practices and serves to enhance students' understanding of the visual representation of force fields in physics. The complete PMFF test is provided in Supplemental Material [52].

To ensure content validity, the test questions were thoroughly reviewed and refined by two professors, with multiple rounds of discussion and revisions conducted in collaboration with graduate students. The final version of the PMFF test was deemed scientifically sound and appropriate for assessing college-level students' understanding of the subject matter. For face validity, nine physics-major college students were interviewed during the revision process. Each student viewed the test questions on a computer screen and was asked to describe their understanding before answering and to explain their reasoning afterward. These interviews focused on identifying ambiguities in the questions rather than evaluating student performance. Both experts and students found the final content and format of the questions appropriate and relevant for measuring PMFF concepts.

To assess the reliability and validity of the PMFF test, a sample of 330 college students majoring in physics at a teacher training university in China voluntarily participated in the study. This group was independent of the participants involved in the eye-tracking experiment, ensuring no overlap between the two samples. Of these participants,

54.9% were female and 45.1% were male. The PMFF test was administered on site as electronic questionnaires, with no time restrictions for completion.

The distribution of students' test scores was shown in Fig. S1 (Supplemental Material [52]). As indicated in Table S1, the average difficulty and discrimination values for all questions were 0.400 and 0.581, respectively, both within acceptable ranges. All item discrimination values exceeded 0.3, demonstrating satisfactory discriminatory power [53]. Point-biserial correlations for the items ranged from 0.496 to 0.670, indicating good consistency between individual items and the overall test. Typically, an acceptable range for point-biserial correlations falls between 0.3 and 0.7, with all items exceeding the minimum threshold of 0.2 [54]. Moreover, Cronbach's α coefficient indicated that deletion of any single item in PMFF did not significantly increase α above the full test value of 0.756. The results indicated that nine items were suitable.

The reliability of the PMFF test was evaluated through Cronbach's α coefficient. The test's construct validity was assessed first via exploratory factor analysis (EFA, $N = 90$), followed by confirmatory factor analysis (CFA, $N = 240$) to further verify the test's underlying structure. The two groups of datasets used for EFA ($N = 90$) and CFA ($N = 240$) were randomly selected from the total sample ($N = 330$), which ensures the consistency of sample constructs.

To verify the construct validity of the PMFF test, EFA was conducted using principal component analysis and varimax rotation. The necessary assumptions for EFA were satisfied. The Kaiser-Meyer-Olkin (KMO) was 0.624, and Bartlett's test of sphericity was 255.927, which was significant ($p = 0.000$), meaning that the sample size was

adequate for the EFA. For each item, the factor on which it loaded most strongly was identified as the item's appropriate factor. As shown in Table S2 in Supplemental Material [52], the three factors can be regarded as the three constructs that the PMFF test claims to measure, namely (i) field of a point mass or charge, (ii) uniform force field, and (iii) uniform magnetic field. Besides, nine items exhibited factor loadings above 0.40, indicating satisfactory contributions to the respective factor and providing preliminary evidence of construct validity. The total explained variance was 62.0%, suggesting that the three factors adequately represented the constructs measured by the test.

To examine the validity of the PMFF test, CFA was used. To check the model fit, the goodness-of-fit indices were used. Figure S2 (see Supplemental Material [52]) illustrates the first-order CFA model, which comprises three dimensions (constructs) and nine items. Among these items, Q5 showed the lowest factor loading (0.47), while Q1 exhibited the highest (0.92). Two-headed arrows in the figure denote covariance between the constructs.

Table S3 in Supplemental Material [52] presents the goodness-of-fit indices, including the ratio of chi-square to degrees of freedom ($\chi^2/\text{d.o.f.}$), goodness-of-fit index (GFI), comparative fit index (CFI), Tucker-Lewis Index (TLI), and root mean square error of approximation (RMSEA). Generally, acceptable model fit required that $\chi^2/\text{d.o.f.}$ was less than 3, GFI and TLI were both above 0.90, and RMSEA was less than 0.08 [55]. As shown in Table S3, all indices fell within these recommended ranges, indicating that the scale demonstrated strong validity.

The reliability of the inventory was evaluated using Cronbach's α , as shown in Table S4 in Supplemental Material [52]. The test achieved an overall Cronbach's α of 0.756, indicating good internal consistency [56].

Table S5 in Supplemental Material [52] reported descriptive statistics of three subscales of the PMFF test. The mean score of the whole test was 3.600. Because the number of items varied across subscales, average item scores (ranging from 0 to 1) were calculated for each subscale to allow meaningful comparison. Based on the means per item, students showed relatively lower performance in the field of a point mass or charge and uniform magnetic field subscales, suggesting persistent difficulties in these field contexts. In contrast, students performed better in the uniform force field subscale, with a higher mean item score of 0.706.

In conclusion, the PMFF test has demonstrated basic validity and reliability and was subsequently employed to investigate students' learning difficulties related to PMFF in the current study by triangulated analysis of data from eye-tracking and quantitative and qualitative measures.

D. Eye-tracking apparatus

Eye movements were recorded with an Eyelink 1000 Plus desktop remote eye-tracking system at a sampling rate

of 1000 Hz. Participants were seated approximately 50 cm in front of the monitor. The monitor's diagonal viewing size was 19 inches with a 1024×768 pixel resolution. The Eyelink 1000 Plus system captured data with an accuracy of less than 0.5° of visual angle. An eye movement was classified as a saccade (i.e., a rapid movement between fixations) if the eye's acceleration exceeded $8000^\circ/\text{s}^2$ and the velocity surpassed $30^\circ/\text{s}$. Otherwise, the eye movement was recorded as part of a fixation (i.e., when the eye remains relatively stationary at a specific spatial location).

E. Data collection and analysis

1. Test score data

The answer coding of the items was dichotomous, with each item scored as 1 point if only the correct answer(s) were selected and 0 points otherwise. In analysis, all mean scores were normalized to a range of 0–1. For evaluation of item features, high mean scores indicated easy items, while low mean scores reflected difficult ones. To further analyze students' understanding of different answer choices, the percentage of students selecting each option for every item was calculated, which provided detailed distributions of student responses.

2. Eye-tracking data

Recorded eye-movement data were analyzed using Data Viewer software, which calculated the fixation time, fixation count, and the number of revisits for each defined AOI. As shown in Fig. 2, each item included five rectangular AOIs, including one AOI on the text of the question and four AOIs on the four choices. The question text AOI denoted different force fields, while the four option AOIs corresponded to four distinct types of motion: Option A for uniform linear motion, option B for uniformly accelerated rectilinear motion, option C for uniformly accelerated curvilinear motion, and option D for uniform circular motion.

Three eye-tracking measures, including fixation time, fixation count, and number of revisits, were analyzed. Fixation time and count referred to the total duration and frequency with which a subject fixated on a given AOI. The number of revisits, calculated as the frequency of a participant's gaze returning to a previously viewed AOI from other AOIs.

Since the eye-tracking metrics did not satisfy the normality assumption required for parametric tests, and the independent variables (contexts and concepts) involved more than two groups, neither parametric tests (t tests or one-way analysis of variance) nor nonparametric methods limited to two-group comparisons (Mann-Whitney U tests) were appropriate. Thus, the Kruskal-Wallis test, a nonparametric method for comparing multiple groups, was used to compare the statistical significance of the measures across different contexts and concepts. The Kruskal-Wallis

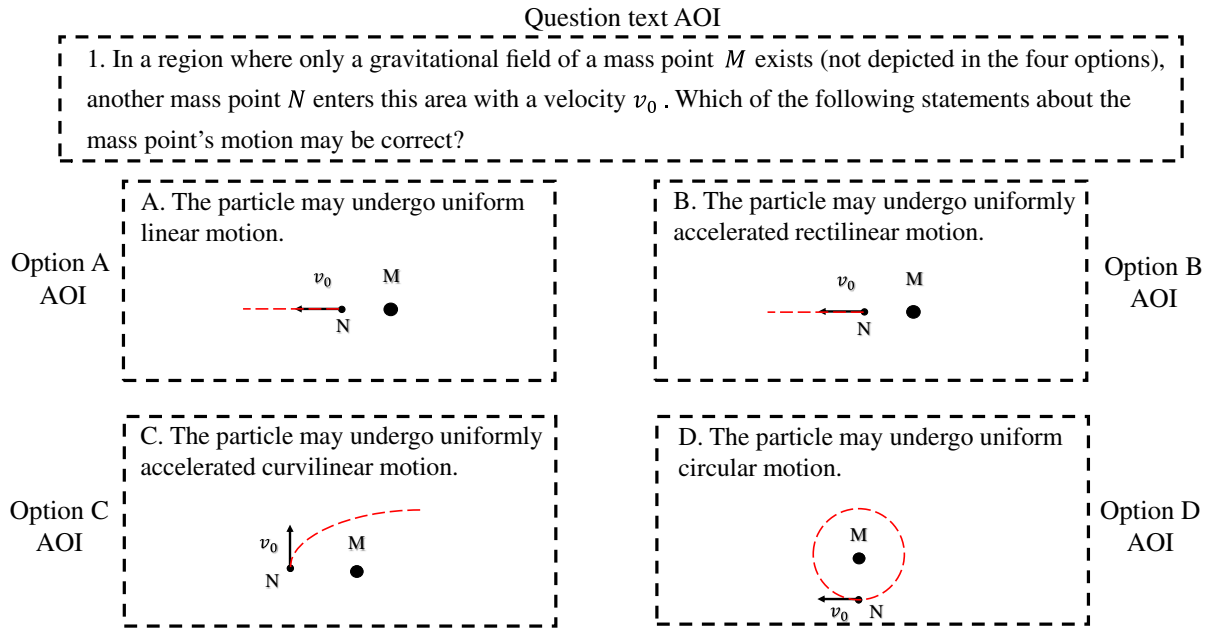


FIG. 2. An example item (Q1) from the PMFF test is shown. Each item included five predefined areas of interest (AOIs), marked by dashed lines that were invisible to students during the test. These AOIs were used to focus analysis on specific regions of the test items, aiding in the systematic evaluation of students' attention and response patterns.

test computed the H statistic to derive the corresponding p value. A p value below 0.05 indicated that at least one pair of groups exhibited a significant difference. However, since the Kruskal-Wallis test did not identify which specific groups differed, the *post hoc* pairwise comparisons of medians were performed using Dunn's test [57]. These pairwise comparisons used the Z statistic, with Bonferroni correction applied to control the false positive rate associated with multiple comparisons. If the adjusted p value remained below 0.05, the difference between the two groups was considered statistically significant.

To gain deeper insights into students' thinking processes, lag sequential analysis (LSA) was utilized to analyze the transition patterns of visual attention across various AOIs [58–60]. We analyzed the sequence of fixation points to calculate the transitional frequency, transitional probability (reflecting the likelihood of a visual transition from one AOI to another, as illustrated in Fig. 7), and the adjusted residuals (z scores). These calculations were performed using the General Sequential Querier (GSEQ) software [61], a toolbox developed by Bakeman and Quera for analyzing interactive behaviors, to explore the transitional patterns of multiple concepts in diverse contexts.

3. Interview data

Each student's interview recording was transcribed and analyzed following Mayring's qualitative content analysis methodology [62]. The transcripts were examined to identify alternative conceptions associated with each option in the nine test items. These alternative conceptions were

categorized based on their respective contexts and underlying scientific concepts and subsequently summarized for each concept. Through collaborative discussions between two coders, the alternative conceptions across various contexts were refined and finalized, as detailed in Table IV. Following a recoding process, interrater reliability was calculated and found to be high, with a Cohen's kappa of 0.89, indicating strong agreement between the coders.

IV. RESULTS

A. Student performances

The item score was measured on a scale from 0.00 (the most difficult item) to 1.00 (the least difficult item). The histogram in Fig. 3 displayed these results in descending order of item score, ranging from 0.91 (Q2) to 0.29 (Q1, Q7). Items were classified as low score when scoring below 0.45 and high score when scoring above 0.75.

The scores varied significantly across different categories of item contexts. Items in the uniform force field context (Q2, Q4, Q6) had high scores, indicating strong student performance in this area. In contrast, items in the contexts involving a field of point mass or point charge (Q1, Q3) and the uniform magnetic field (Q5, Q7, Q8, Q9) received lower scores, suggesting that these contexts posed greater challenges for students. Notably, while Q5, Q7, Q8, and Q9 involved composite fields including the uniform gravitational or electric field and the uniform magnetic field, subsequent student interviews revealed that difficulties primarily stemmed from the magnetic field components. This finding suggests that uniform magnetic fields

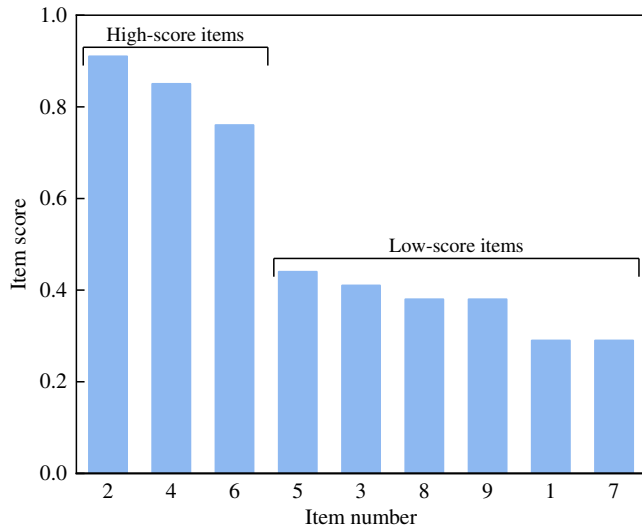


FIG. 3. Histogram of the scores for all items used. The nine items (Q1–Q9) were ordered by the item score from high (left) to low (right).

served as the primary conceptual barrier in these four field contexts.

Table III provides a detailed summary of the distribution of students' responses across various options, shedding light on their conceptual understanding patterns. Students demonstrated strong comprehension of particle motion in the uniform force field context, as evidenced by high scores across all four types of motion. However, notable challenges emerged in the fields of point mass or point charge and uniform magnetic fields. In the field of a point mass or charge, students struggled particularly with uniformly accelerated motion: 44% of students incorrectly identified uniformly accelerated rectilinear motion in Q1, and 53% had difficulties in determining uniformly accelerated curvilinear motion.

Similarly, students encountered significant challenges in the context of uniform magnetic fields. The correct identification rates for uniformly accelerated curvilinear motion

were relatively low, with only 47%, 56%, and 53% of students answering Q7, Q8, and Q9 correctly, respectively. For Q5, which has two correct answers, uniform linear motion and uniform circular motion, only 62% of students correctly identified uniform linear motion as a correct answer. Additionally, a notable proportion of students selected incorrect options, with 24% mistakenly choosing uniformly accelerated curvilinear motion.

These results highlighted specific conceptual barriers, particularly in understanding motion types within the uniform magnetic field, where students consistently struggled across multiple items. Overall, the analysis revealed that students' most persistent difficulty lay in comprehending uniformly accelerated curvilinear motion in the field of a point mass or charge and uniform magnetic field.

B. Patterns in eye-tracking data

The analysis of eye movement data focuses on students' typical scan paths, consisting of fixations and saccades, which can shed light on how students allocate their attention while solving problems. An example of the scan paths of student 14 is presented in Figs. 4(a)–4(c) for three different contexts: (a) the uniform force field, (b) the field of a point mass or charge, and (c) the uniform magnetic field. In these figures, orange circles denote fixation locations, with larger circles signifying longer fixation durations. The solid lines connecting successive fixations represent saccades, and distinct AOIs are marked with black dashed lines.

In Fig. 4(a), the scan path for the uniform force field context is relatively straightforward, with fewer fixations and revisits compared to Figs. 4(b) and 4(c). The student concentrated primarily on the question text and option A, as indicated by more circles and solid lines in those areas. By contrast, Fig. 4(b) reveals a higher number of overall fixations and saccades, suggesting that the student found the point mass or charge context more challenging. Specifically, there was increased attention to the question

TABLE III. Percentages of students selecting each option (four types of motions) per item. The correct answers are marked with an asterisk (*). The questions allow multiple responses, and therefore, the sum of the percentages is larger than 1.

Context of force field	Item	Uniform linear motion (%)	Uniformly accelerated rectilinear motion (%)	Uniformly accelerated curvilinear motion (%)	Uniform circular motion (%)
Uniform force field	Q2	3	97*	94*	0
	Q4	6	94*	97*	9
	Q6	91*	97*	88*	6
Field of a point mass or charge	Q1	9	44	53	91*
	Q3	0	41	29	94*
Uniform magnetic field	Q5	62*	0	24	91*
	Q7	91*	88*	47*	12
	Q8	88*	88*	56*	12
	Q9	82*	91*	53*	74*

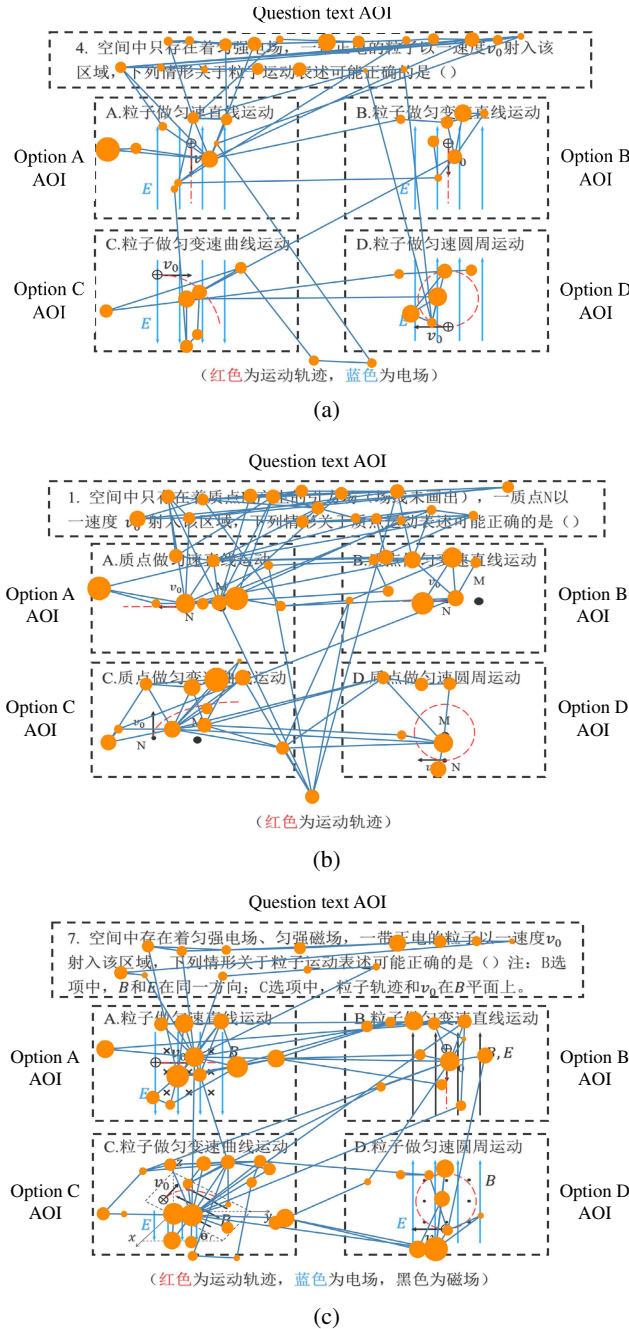


FIG. 4. The scan paths of student 14 are shown: (a) uniform force field context, (b) the field of a point mass or charge context, and (c) uniform magnetic field context. Orange circles represent fixations, with larger circles corresponding to longer fixation durations, while blue solid lines indicate saccades.

text, option A, and especially option C. Similarly, Fig. 4(c) also shows more fixations and saccades than Fig. 4(a), implying that the student faced difficulties in the uniform magnetic field context. Here, the student devoted more attention to option A and option C; compared to Fig. 4(b), attention to option C increased while focus on the question text decreased. Notably, the student appeared to struggle

with option C in both the point mass or charge and uniform magnetic field contexts, while the uniform magnetic field itself received relatively less focus.

These qualitative observations of fixation and scan patterns offer insights into the student's thought processes and align with their performance. The following sections will detail quantitative analyses of these patterns to draw more definitive conclusions.

1. AOI's fixation time and fixation count

Fixation time and count reflected the distribution of attention [15], which showed that longer fixation time and higher fixation count were related to higher difficulty of conceptual understanding [63]. A Kruskal-Wallis test was conducted to determine if there were significant differences in the average fixation time across the varying force field contexts. The results indicated that the differences in force field contexts significantly impacted the average fixation time, $H(2) = 68.55$, $p < 0.001$. The median fixation time for items within the uniform magnetic field ($M_{dn} = 58483$ ms) was significantly longer than that for items in the field of a point mass or charge ($M_{dn} = 45252$ ms). Additionally, the fixation time for the field of a point mass or charge was significantly longer than that for the uniform force field ($M_{dn} = 34599$ ms).

To further explore the distribution of attention across diverse AOIs within various contexts, Kruskal-Wallis tests (H statistic) and Dunn's tests (Z statistic) were conducted, as illustrated in Fig. 5. In the figure, the AOIs are marked with specific colors for differentiation: gray represents the question text AOI (force field), blue indicates option A AOI (uniform linear motion), green corresponds to option B AOI (uniformly accelerated rectilinear motion), red is used for option C AOI (uniformly accelerated curvilinear motion), and purple represents option D AOI (uniform circular motion). Medians of fixation time for different AOIs are indicated by black horizontal lines in the box.

Differences in fixation time distributions between high- and low-score items were analyzed. For high-score items within the uniform force field context (Fig. 5, left), significant differences in fixation time across different concepts were found using the Kruskal-Wallis test ($H(4) = 100.24$, $p < 0.001$). Pairwise comparisons of the medians were conducted using *post hoc* Dunn's tests. The results revealed that students spent the most time fixating on question text ($M_{dn} = 9510$ ms), followed in decreasing order by fixation times for option A ($M_{dn} = 6744$ ms), option B ($M_{dn} = 5720$ ms), option C ($M_{dn} = 5720$ ms), and option D ($M_{dn} = 4610$ ms). Significant differences were observed among these fixation times.

Compared to the high-score items (Fig. 5, left), low-score items exhibited distinct attention distribution (Fig. 5, middle and right). For items within the field of a point mass or charge context (Fig. 5, middle), the Kruskal-Wallis test identified significant differences in fixation time across

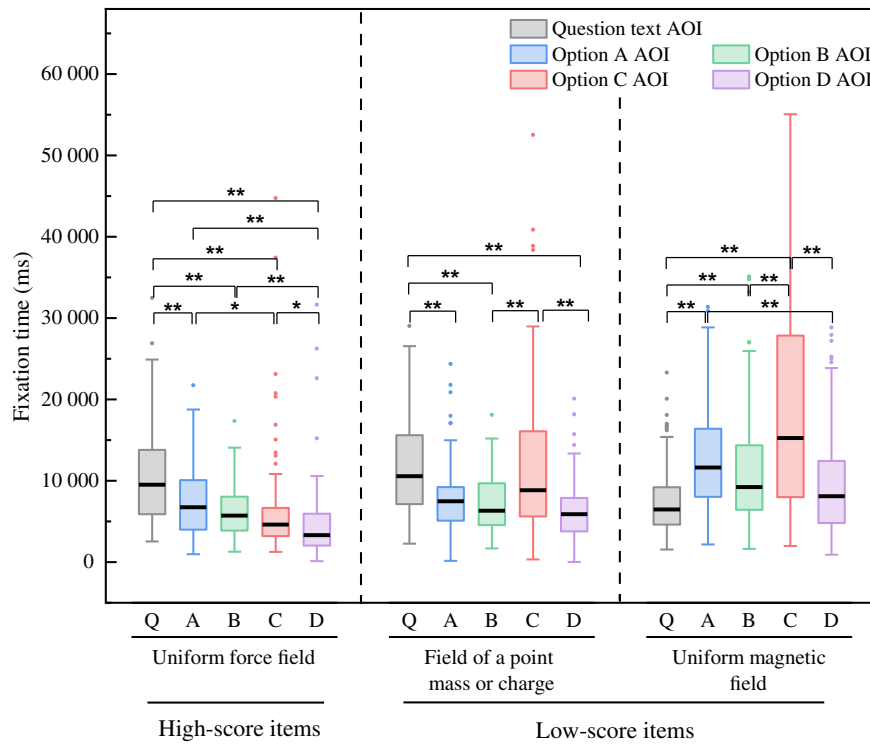


FIG. 5. Fixation time for five AOIs (representing different concepts) within three force field contexts, evaluated across all students. One or two asterisks indicate significantly different pairwise comparisons at levels of $p < 0.05$ or $p < 0.01$, respectively. The black horizontal line depicts the median of the data. Q refers to the question text AOI, and A, B, C, and D refer to their corresponding option AOIs.

various concepts [$H(4) = 47.20$, $p < 0.001$]. *Post hoc* Dunn's tests revealed that the question text still received the most attention. However, the fixation time for option C increased significantly, exceeding that for option B ($Z = -3.36$, $p < 0.01$), and not differing from that for the question text and option A.

For items within the uniform magnetic field context (Fig. 5, right), significant differences in fixation time across AOIs were also observed, $H(4) = 102.77$, $p < 0.001$. Pairwise comparisons of the medians, conducted using Dunn's test, revealed a distinct pattern. The fixation time for option C also increased significantly, exceeding that for option B ($Z = -4.41$, $p < 0.001$) and remaining comparable to that for option A. Notably, the fixation time for question text decreased significantly, becoming shorter than that for option A ($Z = -6.96$, $p < 0.001$), option B ($Z = -4.59$, $p < 0.001$), and option C ($Z = -9.00$, $p < 0.001$).

It could be found that in both the field of a point mass or charge and uniform magnetic field, students devoted significantly more attention to option C (uniformly accelerated curvilinear motion). However, their attention to the uniform magnetic field itself (question text) was minimal.

Similar results and conclusions were obtained in the analysis of fixation count [52], which were not

detailed here but aligned with the findings of Susac *et al.* (2019–2023), indicating that fixation time and fixation count showed similar response patterns [45,64,65].

2. AOI's revisit

The number of times a student revisited an AOI has been considered to reflect the level of confusion regarding the concept, with more revisits indicating the difficulties in comprehension [66]. A Kruskal-Wallis test was conducted to determine whether there were significant differences in revisits across the different contexts of force fields. The results showed significant differences among the three force field contexts [$H(2) = 15.00$, $p < 0.001$]. Specifically, items in the field of a point mass or charge ($M_{dn} = 33.5$) had more revisits compared to those in the uniform magnetic field ($M_{dn} = 27.5$) and the uniform force field ($M_{dn} = 24$).

To further investigate cognitive processing across various AOIs within different force field contexts, multiple Kruskal-Wallis tests and Dunn's tests were conducted, as shown in Fig. 6. The AOIs were marked with the same colors as in Fig. 5. In Fig. 6, the revisit distributions between high- and low-score items were compared.

For high-score items within the uniform force field context (Fig. 5, left), significant differences in revisit across

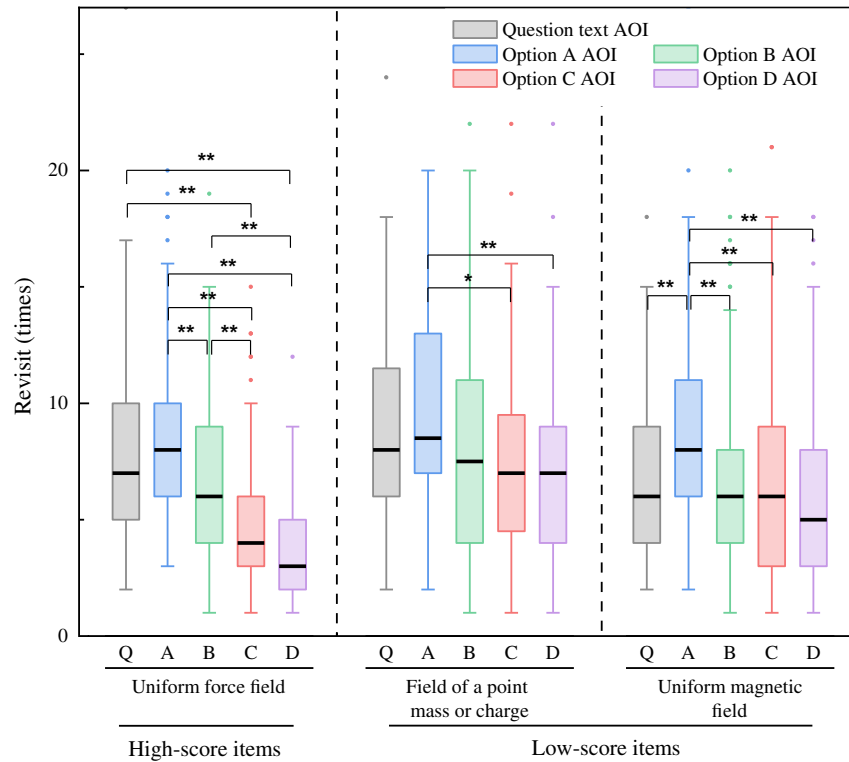


FIG. 6. Revisits for five AOIs (denoting different concepts) within three force field contexts were evaluated. One or two asterisks indicate significantly different pairwise comparisons at levels of $p < 0.05$ or $p < 0.01$, respectively. The black horizontal line depicts the median. Q refers to the question text AOI, and A, B, C, and D refer to their corresponding option AOIs.

different concepts were identified, $H(4) = 130.98$, $p < 0.001$. For the results of pairwise comparisons of the medians, students revisited the option A ($M_{dn} = 8$) and question text ($M_{dn} = 7$) the most, followed in decreasing order by option B ($M_{dn} = 6$), option C ($M_{dn} = 4$), and option D ($M_{dn} = 3$), with significant differences observed among these revisits.

Low-score items (Fig. 6, medium and right) demonstrated a set of differences in revisit distribution compared to high-score items (Fig. 6, left). For items within the field of a point mass or charge context (Fig. 6, medium), there were significant differences in the number of revisits across different concepts [Kruskal-Wallis test, $H(4) = 18.57$, $p < 0.001$]. Nonetheless, *post hoc* Dunn's tests were used to perform pairwise comparisons of the medians, revealing no significant differences among most AOIs and reflecting generally high revisits across all AOIs.

For items within the uniform magnetic field context (Fig. 6, right), significant differences in the number of revisits across concepts were found [Kruskal-Wallis test, $H(4) = 46.29$, $p < 0.001$]. Dunn's tests for pairwise comparisons of the medians revealed patterns similar to those observed in fixation time. First, revisits for option C (uniformly accelerated curvilinear motion) increased significantly, with no difference compared to revisits for option B. Second, the number of revisits for the question text (the force field) decreased significantly, being fewer

than those for option A ($Z = -4.19$, $p < 0.001$), and showing no significant difference when compared to option B, option C, and option D.

To quantitatively analyze students' saccade patterns, lag sequential analysis (LSA) was conducted to explore students' eye movement transition patterns during problem solving, with an emphasis on significant attentional shifts between AOIs [18]. Significant transition frequencies between AOIs were determined using the adjusted residuals (z scores) across the three force field contexts and visualized in Fig. 7. These analyses suggested which AOIs were frequently in competition. Figures 7(a)–7(c) illustrate the visual transitional patterns for the uniform force field, the field of a point mass or charge, and the uniform magnetic field, respectively. Arrows connecting two AOIs represent significant visual transitions from one AOI to the other, with the numbers beside the arrows indicating transition probabilities. For instance, in Fig. 7(a), the probability of transitioning from the force field to the uniform linear motion is 0.57, while the probability of transitioning from the uniform linear motion to the force field is 0.51. AOIs were marked with black rectangles. Additionally, all questions required students to analyze the spatial distribution of force fields. During such analysis and thinking, students may look at empty areas to visualize forces acting on particles. Thus, the empty areas outside the AOIs were also included in our analysis.

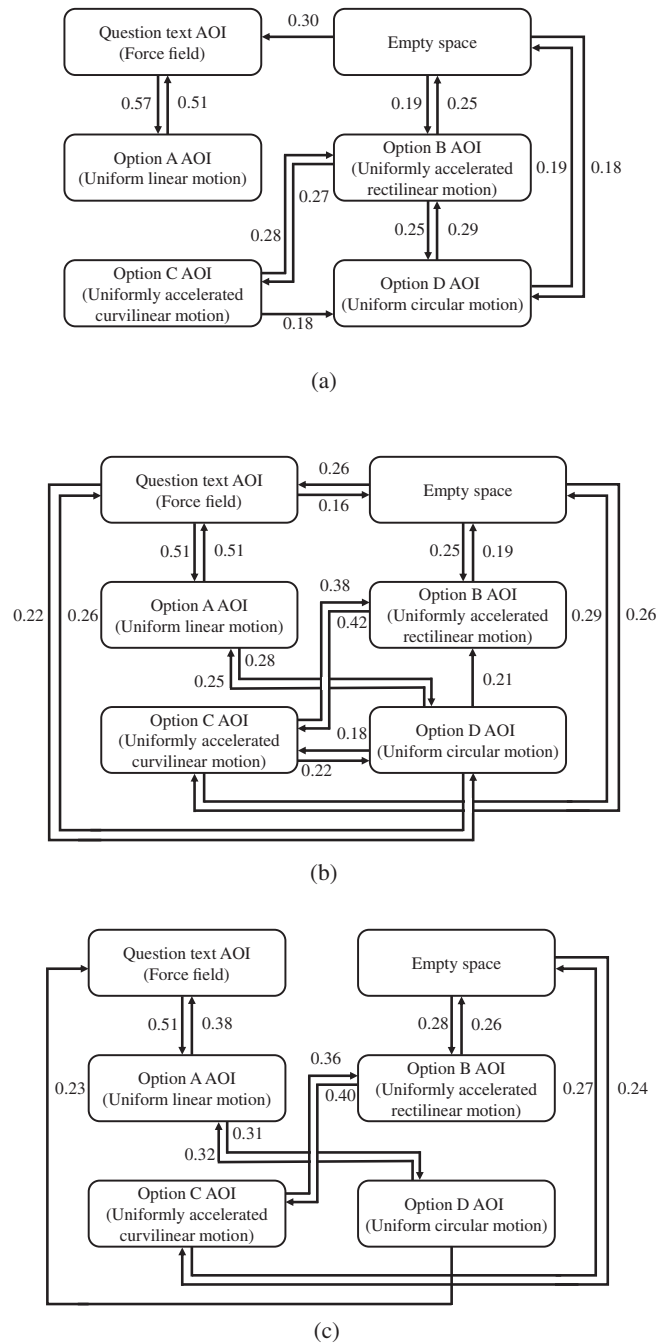


FIG. 7. Visual transitional patterns for three contexts of the force field. (a) Uniform force field. (b) Field of a point mass or charge. (c) Uniform magnetic field.

By comparing the three visual transitional patterns in Figs. 7(a)–7(c), differences in patterns of LSA diagrams were observed among the uniform force field, the field of a point mass or charge, and the uniform magnetic field. Considering that few difficulties were reported for the uniform force field, its transition pattern appeared straightforward and clear. Significant back-and-forth patterns were observed between the concepts of force

field and uniform linear motion; uniformly accelerated rectilinear motion and uniformly accelerated curvilinear motion; and empty space and uniformly accelerated rectilinear motion (Force field $\leftrightarrow$ Uniform linear motion, Uniformly accelerated rectilinear motion $\leftrightarrow$ Uniformly accelerated curvilinear motion, and Uniformly accelerated rectilinear motion $\leftrightarrow$ Empty space). Comparing this with the other two force field contexts, students' learning difficulties became evident.

For items within the field of a point mass or charge, students showed highly complex transition patterns, with high transition probabilities between nearly all AOIs. Notably, the transition probabilities between uniform circular motion and other AOIs increased significantly. For items within the uniform magnetic field, students frequently transitioned between uniformly accelerated curvilinear motion and either uniformly accelerated rectilinear motion or the empty space (Uniformly accelerated curvilinear motion $\leftrightarrow$ Uniformly accelerated rectilinear motion, Uniformly accelerated curvilinear motion $\leftrightarrow$ Empty space). In addition, they were more likely to visually transfer back and forth between uniform linear motion and uniform circular motion (Uniform linear motion $\leftrightarrow$ Uniform circular motion). However, students were less likely to transition from the force field to other AOIs.

C. Alternative conceptions identified from interview data

Table IV presents the learning difficulties students encountered when addressing the PMFF, based on a qualitative analysis of the interview data. While students may have demonstrated the same alternative conception across multiple items, each category was counted only once per participant in the quantitative analysis, regardless of its frequency in the transcript. The analysis focused on identifying whether a participant experienced specific learning difficulties, not on the statistical frequency of these difficulties.

No students reported any difficulties with the mathematics involved, such as the vector superposition of multiple forces. Instead, the students' alternative conceptions were primarily focused on the characteristics of force fields and the relationship between force and motion.

In the context of the uniform force field, students reported no issues with the force field itself, and the majority had no difficulty understanding the four motions within it. However, since the uniform gravitational field was not explicitly depicted in the four options, a small percentage of students (9%) either subconsciously overlooked its presence when gravity was involved or incorrectly assumed its presence when it was absent. For instance, when solving Q4, which involves only a uniform electric field, S14 assumed that the particle was subject to the gravity, stating: "The particle experiences both an electric force and gravity ..."

TABLE IV. Summary of perceived alternative conceptions regarding the PMFF. The number and percentage of students ($N = 34F$) are presented. The symbol “.” signifies that the force field context does not involve this alternative conception.

Alternative conceptions about the PMFF	Numbers (percentage) of students		
	Uniform force field	Field of a point mass or charge	Uniform magnetic field
Uniform force field			
Ignoring or defaulting to the gravity (because it is not drawn in the four options)	3(9)	.	6(18)
Force field of a point mass or charge			
The gravitational force on a particle remains constant regardless of the distance	.	10(29)	.
The direction of the force acting on a particle can be in any direction	.	3(9)	.
Confusion with the uniform force field: The force acting on a particle is assumed to be vertically downward	.	4(12)	.
Confusion with the uniform force field: Both gravity and the gravitational force are analyzed simultaneously	.	1(3)	.
Uniform magnetic field			
As long as the particle is in a uniform magnetic field, it will experience a force	.	.	13(38)
As long as the velocity changes, experienced by the particle will also change	.	.	34(100)
“.” and “×” only represents B	.	.	19(56)
Uniformly accelerated rectilinear motion			
As long as F and v are in the same direction, the particle can undergo uniformly accelerated rectilinear motion (neglecting the assessment of the magnitude of acceleration)	1(3)	17(50)	0
Uniformly accelerated curvilinear motion			
As long as F is directed toward the concave side of the trajectory, the particle can undergo uniformly accelerated curvilinear motion (neglecting the assessment of the magnitude of acceleration)	3(9)	20(59)	25(74)

In the context of the field of a point mass or charge, students exhibited several alternative conceptions about the force field characteristics. When analyzing uniform accelerated motion, some students indicated unfamiliarity with this field context. Specifically, 29% of students incorrectly assumed that the force acting on a particle remained constant regardless of the distance between the object and the point mass or charge:

S24 : (Q1) The particle experiences a constant horizontal force ... I am uncertain about the type of force generated by the gravitational field of a point mass.

Additionally, 9% of students struggled to determine the direction of the force, thinking it could point in any direction:

S8 : (Q1) The gravitational force on the particle could be directed either inward or outward.

S9 : (Q1) I am unsure about the concept of the gravitational field. Consequently, the force could act in any direction, and the particle might exhibit any type of motion.

Some students confused the field of a point mass or charge with the uniform force field, assuming the direction of force on a particle was always vertically downward

(12%) and confused with gravity and gravitational force (3%), thinking that they may be two forces:

S4 : (Q1) The gravitational field should point downward ... I am not well-acquainted with the gravitational field.

S9 : (Q1) The particle is subject to both gravitational force and the gravity.

Furthermore, several students failed to assess whether the magnitude of acceleration remained constant. When force and velocity were aligned, uniform accelerated rectilinear motion was incorrectly concluded to be possible by 50% of students. Moreover, 59% of students erroneously believed that as long as the force pointed toward the concave side of the trajectory, the particle could undergo uniformly accelerated curvilinear motion. For example,

S21 : (Q3) The particle experiences a horizontal force (aligned with its velocity), allowing it to undergo uniformly accelerated linear motion ... When the force acting on the particle is not aligned with its velocity, the particle may exhibit uniformly accelerated curvilinear motion.

In the context of the uniform magnetic field, students demonstrated several persistent alternative conceptions.

About 38% of students incorrectly believed that the presence of a magnetic field would always cause a particle to experience a force:

S3 : In a magnetic field, a particle would experience a force ...

In the context of uniformly accelerated curvilinear motion, all students assumed that any change in velocity would lead to a change in the Lorentz force:

S15 : When the velocity and Lorentz force have a certain angle between them, the Lorentz force will inevitably change.

Additionally, 56% of the students misinterpreted the symbol “.” and “×,” thinking that these symbols solely represented the magnetic fields.

S30 : (Q9, option C) The particle is subjected to a downward Lorentz force and a downward electric force ... Wait, the blue “.” and “×” represent an electric field, not a magnetic field.

R : Did you assume that the “.” and “×” represent a magnetic field at that time? Why?

S30 : Yes ... in high school physics exercises, I have only encountered “.” and “×” notation for the magnetic field. I subconsciously associated them with the magnetic field.

A small number of students (12%) overlooked the uniform gravitational force due to the absence of a visual representation of the gravitational field. Furthermore, a large portion of students struggled to determine the motion accurately. Specifically, 74% of students expressed difficulty determining whether the magnitude of acceleration remained constant, asserting that as long as the force pointed toward the concave side of the trajectory, the particle could undergo uniformly accelerated curvilinear motion. For example,

S3 : (Q5, option C) The particle experiences a Lorentz force that is not aligned with the direction of velocity, so it can undergo uniformly accelerated curvilinear motion.

No students revealed any alternative conceptions about uniformly accelerated rectilinear motion in the context of the uniform magnetic field.

V. DISCUSSION

In this study, we employed the PMFF test to investigate students’ conceptual understanding and learning difficulties in three force fields. The results showed that students performed relatively well in the familiar context of a

uniform force field but faced substantial challenges in the field of a point mass or charge and in a uniform magnetic field. In the Chinese physics curriculum, instruction tends to heavily emphasize uniform force fields—most commonly free fall and projectile motion—while the point mass or charge field and uniform magnetic field receive relatively less attention, often limited to uniform circular motion. The following sections delve deeper into these learning difficulties through a detailed analysis of test scores, interview responses, and eye-tracking data.

A. No difficulty in the familiar context of the uniform force field

Analysis of the three items related to the uniform force field showed that students demonstrated a good understanding of both the force field concept and its corresponding motions, as indicated by high test scores. Interview responses corroborated this observation, with students reporting no significant difficulties in this area. Eye-tracking data reinforced these findings by revealing shorter fixation durations and fewer revisits for these items compared to others. Moreover, the pattern of eye-tracking metrics across different AOIs was consistent with standard problem-solving strategies, indicating that students efficiently extracted information from the question text and made prompt decisions during the solving process.

B. Student difficulties in unfamiliar contexts

While students were generally proficient in determining particle motion in the uniform force field, they encountered significant difficulties in the contexts of the field of a point mass or a point charge and the uniform magnetic field.

1. Student difficulties in uniform accelerated motion in the field of a point mass or charge context

For items related to the field of a point mass or a point charge, students encountered significant difficulties, particularly with uniformly accelerated motion. Scores on these items were consistently below 0.45, with frequent errors observed in both uniformly accelerated rectilinear motion and curvilinear motion. Interviews revealed several underlying causes for these challenges. One primary issue was the inappropriate generalization of concepts from uniform force fields to the field of a point mass or a point charge. This conceptual conflation led to alternative conceptions, such as the mistaken belief that gravitational force remains constant regardless of distance or that its direction is arbitrary or always vertically downward.

Additionally, students often neglected to evaluate the characteristics of uniformly accelerated motion, focusing instead on whether the particle’s trajectory was linear or curvilinear. This oversight likely stemmed from their extensive exposure to free fall and projectile motion within uniform force fields. Without a solid understanding of

uniformly accelerated motion principles in the field of a point mass or charge, students frequently relied on pattern recognition, matching familiar trajectory shapes rather than analyzing fundamental elements like the magnitude of F_{net} . This tendency to base decisions on surface features rather than underlying physical principles underscores the need for more targeted instruction on the unique properties of different force fields.

Eye-tracking data provided additional insights into these learning difficulties. Items in this context exhibited longer total fixation times and a higher number of revisits, indicative of greater cognitive challenges. These findings align with previous research, which suggests that increased fixation durations often correspond to heightened comprehension demands during reading and problem-solving tasks [63]. Specifically, uniformly accelerated curvilinear motion attracted particularly high fixation times, reflecting significant conceptual processing demands. Frequent revisits to areas related to the force field and types of motion also pointed to cognitive conflict, as students grappled with reconciling their understanding of point mass or charge fields with their more familiar knowledge of uniform force fields.

2. Student difficulties in uniformly linear motion and uniform accelerated curvilinear motion in the uniform magnetic field context

In the context of uniform magnetic fields, students faced significant difficulties with two types of motion: uniform linear motion and uniformly accelerated curvilinear motion. These items consistently yielded low scores (below 0.45), with high rates of incorrect responses observed for uniform linear motion in Q5 and for uniformly accelerated curvilinear motion in Q5, Q7, Q8, and Q9.

Interviews provided valuable insights into these challenges. For uniform linear motion, students often relied on memorization of formulas for uniform magnetic fields without fully understanding the relationship between the Lorentz force and the angle between v and B . A prevalent alternative conception was that particles would experience a Lorentz force merely by being in a magnetic field, regardless of whether the particle was in motion or the direction of its motion.

The difficulties with uniformly accelerated curvilinear motion stemmed from a deeper misunderstanding: the belief that any change in velocity automatically alters the Lorentz force acting on a particle. This belief may arise from teaching strategies at the high school level, where the Lorentz force is often decomposed into components parallel and perpendicular to the magnetic field. While this approach aims to clarify the force's behavior, it may inadvertently obscure the angle dependence between velocity and the magnetic field in determining the magnitude of the Lorentz force. Furthermore, students frequently associated the symbols “.” and “×” exclusively with the magnetic field, likely due to the unvaried, persistent use of

such symbols to represent magnetic fields in many Chinese high school textbooks. This limited interpretation reinforces incorrect assumptions and complicates conceptual understanding, especially when paired with the frequent use of these symbols in problem-solving tasks.

Another observed issue was students' tendency to prioritize determining the particle's trajectory while neglecting the conditions for constant acceleration magnitude. This mirrors patterns of errors seen in uniformly accelerated motion within the field of a point mass or point charge, suggesting a reliance on rote memorization rather than a robust conceptual framework.

Eye-tracking data further substantiated these findings. Items involving uniform magnetic fields exhibited longer fixation times and higher revisit frequencies, highlighting significant learning challenges. Specifically, elevated fixation times and revisits were recorded for uniformly accelerated curvilinear motion, indicating substantial conceptual difficulties.

Notably, fixation times and revisits on the force field itself were surprisingly low, contrasting sharply with the persistent misconceptions revealed in interviews. This finding differed from typical conclusions in eye-tracking education research, where longer fixation durations and more frequent revisits were generally associated with cognitive difficulty in a specific area [16,19,65]. Dual-process theories proposed that cognition involved two distinct thinking systems: a rapid, intuitive process and a slower, analytical reasoning process [67–69]. Analytical reasoning typically involves more cognitive attention during problem solving, with difficulties surfacing either through explicit interviews or higher eye-tracking metrics. In contrast, intuitive errors often went unspoken and required both interview and eye-tracking data to confirm. In this study, the unusually low visual attention, despite clear signs of misunderstanding, suggested that students relied on automatic, unexamined intuitions. These findings underscore the need for targeted instructional strategies that both elicit and address these hidden misconceptions.

3. Surface-feature-based reasoning in two unfamiliar contexts

Many students rely heavily on memorization and lack a deeply integrated understanding of the relationship between motion and force fields [70,71]. When presented with unfamiliar or less typical scenarios, students often revert to superficial reasoning based on memorized features, such as trajectory shapes, rather than applying conceptual knowledge to novel contexts [72,73]. Visual transition patterns, as revealed by LSA, further supported these observations, showing frequent transitions between areas associated with uniform circular motion and other AOIs in the field of a point mass or charge context. This suggested that students viewed uniform circular motion within the field of a point mass or charge as a familiar

anchor and used it as a reference point in their reasoning. In the uniform magnetic field context, decreased transitions between the force field and other AOIs, coupled with an increase in pattern-matching behavior based on familiar surface features, were apparent. For example, transitions were more frequent between uniformly accelerated curvilinear and rectilinear motion, as well as between uniform linear and uniform circular motion. These patterns suggest that students relied on recognizable trajectory features rather than engaging deeply with the underlying principles. These findings highlight the need for instructional strategies that emphasize the distinctive characteristics of particles' motion within different force fields and foster deeper conceptual understanding.

VI. CONCLUSION AND IMPLICATIONS

This study investigated the learning difficulties of physics majors who had completed university-level mechanics and electromagnetism courses, which include the topic of particle motion in force fields. Using a combination of test scores, interviews, and eye-tracking data, we examined students' conceptual understanding across different force field contexts. The findings revealed that students exhibited a strong grasp of particle motion in uniform force fields. However, in the field of a point mass or a point charge, students displayed incorrect beliefs related to uniformly accelerated motion. In the uniform magnetic field context, students struggled to distinguish between uniform linear motion and uniformly accelerated curvilinear motion. Moreover, students tended to rely on surface-feature reasoning rather than developing a deep conceptual understanding.

A. Implications

These findings highlight the persistence of alternative conceptions among university-level physics majors, emphasizing the need for targeted instructional interventions in complex force field contexts, such as the field of a point mass or charge and uniform magnetic fields. Instruction on uniform magnetic fields should stress the critical role of the angle between velocity and the magnetic field in determining the force. It is also important to clarify that the symbols “ $\cdot$ ” and “ $\times$ ” are merely directional indicators, which should be used to represent other fields or vectors in addition to the magnetic field. To foster conceptual change, instructional tasks may present particles' motion across different field contexts to trigger cognitive conflict, deepening their understanding of force and motion relationships. Additionally, the PMFF assessment tool developed in this study provides educators with a valuable diagnostic tool for evaluating students' conceptual understanding of force and motion across different contexts. Finally, in the eye-tracking analysis, unusually low fixation durations and infrequent revisits, when triangulated with interview data, should be taken seriously because

they can signal automatic and unattended misconceptions that require targeted pedagogical interventions.

B. Limitations

Despite the insights gained, several limitations warrant consideration. While the eye-tracking sample size ($n = 34$) is within the acceptable range for physics education research (PER) studies (15–119 participants), it falls below the field's average ($M = 54.4$) [15]. Furthermore, the study's single-institution scope limits the generalizability of the results. Due to the relatively high level of physics knowledge among the participants in this study, the findings may not be directly generalized to other populations, which warrants further investigation. Additionally, due to restrictions of the eye-tracking setup, students were unable to use paper and pencil for calculations or illustration. To mitigate this, motion trajectories were illustrated in the item options to reduce cognitive demands. However, this use of images may have introduced unintended challenges, and it remains unclear whether these visual aids ultimately facilitated or hindered student understanding.

C. Future directions

Future research could address these limitations through several avenues. Expanding the participant pool to include graduate students and teachers would enhance the study's generalizability. Controlled experiments comparing eye-tracking data with and without visual representations of trajectories could clarify their impact on cognitive processing. Additionally, the design of the eye-tracking assessment did not allow students to revisit and revise their responses, which some interviewees noted hindered their ability to correct earlier errors upon reflection. Investigating this phenomenon could offer deeper insights into the cognitive processes underlying physics problem solving and inform strategies for improving learning outcomes.

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DATA AVAILABILITY

We confirm that the data supporting the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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