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Analysis of Preservice Physics Teachers' Thinking Processes in Solving Force Concept Inventory Item Using Eye Tracking

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ABSTRACT

Understanding students' conceptual reasoning in physics cannot be adequately explained through correct or incorrect answers alone, as conventional assessments provide limited information about the cognitive processes underlying problem solving. Although eye-tracking technology has been increasingly applied in educational research, its use to investigate students' visual attention while solving conceptual physics problems, particularly the *Force Concept Inventory* (FCI), remains limited. This study aimed to analyze students' visual attention patterns during the completion of an FCI question using eye-tracking technology. A descriptive study was conducted involving ten undergraduate students in a Physics Education program. Eye-movement data were collected using GazeRecorder with the built-in laptop camera while participants solved one FCI question. The analysis focused on *dwell time*, and heatmap across eight predefined *Areas of Interest* (AOIs). The results indicated that students primarily allocated their visual attention to the problem description and illustration before evaluating the answer options. Students who selected the correct answer generally exhibited greater attention to the correct alternative, whereas those selecting incorrect options devoted more attention to the distractors they ultimately chose. These findings demonstrate that eye tracking provides valuable insights into students' conceptual reasoning beyond conventional test scores and has considerable potential as a diagnostic assessment tool for identifying misconceptions in physics learning.

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1. INTRODUCTION

Physics education is not only intended to enable students to apply mathematical equations to solve problems but also to develop a sound conceptual understanding of natural phenomena. However, numerous studies have shown that fundamental concepts in mechanics, particularly those related to force and motion, remain among the most challenging topics for learners to understand (Faria et al., 2025; G. Liu & Fang, 2016; Taqwa et al., 2022). Misconceptions concerning the relationships among force, velocity, and acceleration continue to be observed among both secondary school students and university students, even after they have received formal instruction (Badruldin & Alias, 2022; Bouzid et al., 2025; Jielili et al., 2026). These findings suggest that successful physics learning should not be assessed solely based on the correctness of students' answers but should also consider the thinking processes they employ while solving physics problems.

One of the most widely used instruments for identifying misconceptions related to force and motion is the Force Concept Inventory (FCI) (Hestenes et al., 1992). The FCI was developed to assess conceptual understanding of Newtonian mechanics through multiple-choice items, in which each distractor is deliberately designed to represent common misconceptions held by learners. Unlike conventional tests that primarily emphasize computational skills, the FCI is intended to evaluate students' conceptual reasoning about physical phenomena. Over the past three decades, the FCI has been extensively employed in physics education research across many countries as a standard instrument for evaluating instructional effectiveness and diagnosing students' misconceptions.

Despite its widespread use, the information obtained from the FCI is generally limited to whether responses are correct or incorrect and which distractors students select. Such outcomes do not reveal the cognitive processes involved when students read the problem, examine the accompanying illustration, compare the answer choices, and ultimately make a decision. Two students may arrive at the same answer through entirely different reasoning processes, while another student may choose an incorrect answer despite attending to the relevant information presented in the problem. Therefore, complementary approaches are needed to uncover the thinking processes underlying problem solving rather than focusing solely on the final responses.

One approach that has gained considerable attention in educational research is eye tracking. This technology enables researchers to record participants' gaze direction, fixation duration, gaze transitions, and sequences of visual attention while completing a task (Ke et al., 2024; Tóthová & Rusek, 2025). Eye-tracking metrics such as fixation duration, fixation count, time to first fixation, scanpath, and revisits can provide valuable insights into how learners process visual information during problem solving. Consequently, eye tracking not only identifies where students direct their attention but also offers evidence of the information-processing strategies they employ throughout the reasoning process.

In recent years, the application of eye tracking in science education research has grown substantially. A literature review conducted by Hahn & Klein (2022) reported that eye-tracking studies in physics education have expanded rapidly, particularly in the areas of mechanics, problem solving, graph interpretation, visual representations, and conceptual assessment. Eye tracking is considered particularly valuable because it provides information that cannot be obtained through written tests or conventional interviews, as it captures learners' visual attention directly during the learning process.

More recent reviews further indicate that eye tracking has become an important methodological approach in science education research. Based on analyses of hundreds of international publications, the technology has been widely used to investigate visual attention, cognitive load, learning strategies, and decision-making processes as learners interact with various scientific representations. These studies consistently demonstrate that patterns of visual attention are closely associated with the quality of learners' conceptual understanding (Tóthová & Rusek, 2025). Recent evidence from higher education indicates the growing use of eye-tracking technology to investigate cognitive processing, attention allocation, engagement, and learning performance across different instructional contexts (Adıgüzel et al., 2026). Recent bibliometric evidence also indicates increasing research interest in applying eye-tracking technology to chemistry and science learning, particularly in relation to learning processes, visual attention, and problem solving (Muna & Bahit, 2023).

Recent research has also demonstrated the potential of webcam-based eye tracking for examining preservice teachers' visual attention during problem-solving tasks. Muna et al. (2025) examined the attentional patterns of preservice chemistry teachers from non-science educational backgrounds while solving chemistry problems using an online webcam-based eye-tracking platform. Their findings showed that participants exhibited different patterns and durations of visual attention that were associated with their problem-solving performance. This study demonstrates the potential of accessible online eye-tracking technology for investigating how preservice teachers allocate attention while processing disciplinary problems.

Although eye-tracking research in physics education continues to expand, its application to the Force Concept Inventory remains relatively limited. Most existing studies have employed eye tracking to investigate numerical problem solving, graph interpretation, or the use of visual representations in physics learning. Studies that specifically integrate eye-tracking data with FCI diagnostic items to examine preservice physics teachers' (PSPTs) thinking processes while solving conceptual problems are still scarce. Recent research has also identified the integration of eye-tracking data with test responses as an emerging area with significant potential to improve the accuracy of diagnosing misconceptions in Newtonian mechanics (J. Liu et al., 2026).

In Indonesia, research on physics misconceptions has primarily relied on diagnostic tests, two-tier tests, and interviews, whereas the application of eye tracking in physics education research remains limited. Consequently, little is known about how students allocate their visual attention to problem statements, illustrations, and answer options when solving conceptual physics questions. Such information could provide deeper insights into students' thinking strategies and assist instructors in designing more effective instructional approaches.

Against this background, the present study employs eye-tracking technology to explore the thinking processes of PSPTs while solving an FCI item related to the concepts of force and motion. The analysis focuses on PSPTs' visual attention patterns across several Areas of Interest (AOIs), including the problem statement, the accompanying illustration, and each answer option. By examining these visual attention patterns, this study aims to reveal the visual strategies that students use to construct conceptual understanding before selecting their answers. The findings are expected not only to enrich the literature on conceptual assessment in physics education but also to provide empirical evidence that can support physics educators in developing more effective instructional strategies to reduce students' misconceptions.

2. METHODS

2.1. Research Design

This study employed a descriptive quantitative research design. This approach was selected because the study aimed to describe the visual attention patterns of PSPTs while solving a conceptual FCI item based on eye-tracking data.

2.2. Participants

The participants consisted of 10 PSPTs enrolled in the Physics Education Program at Universitas Sulawesi Barat. Participants were selected using purposive sampling based on the following criteria: (1) they had completed the Basic Physics and Mechanics courses, (2) they had no visual impairments that could affect the accuracy of eye-tracking recordings, and (3) they voluntarily agreed to participate by signing an informed consent form. The present study was exploratory and descriptive, focusing on identifying individual patterns of visual attention rather than testing population-level hypotheses. Previous eye-tracking research has demonstrated the use of relatively small samples for exploratory investigations of visual attention, while recent methodological research also indicates that no single-sample-size recommendation is applicable to all eye-tracking studies, particularly those involving heatmap and Area of Interest (AOI) analyses (Hoogerbrugge et al., 2025; Selivanova & Krabbe, 2018). Nevertheless, the relatively small sample should be considered when interpreting the findings, as it limits the generalizability of the observed visual attention patterns to a broader population.

2.3. Research Instrument

The research instrument consisted of a single item from the FCI. The use of one FCI item was intended not to assess participants' overall conceptual understanding of Newtonian mechanics, but to enable an in-depth examination of their visual attention while solving a conceptual physics problem. The item was purposively selected because it required participants to integrate verbal information, a visual representation, and multiple answer alternatives. This structure allowed the problem to be divided into distinct AOI for examing how participants allocated their visual attention during problem solving. Previous eye-tracking study in physics education have similarly examined students' visual attention to specific components of conceptual physics problems, particularly diagrams and other task-relevant information (Madsen et al., 2013).

The selected item assessed conceptual understanding of an object's motion under the influence of a constant force and was considered suitable for examining visual attention related to Newton's First and Second Laws of Motion. While participants solved the problem, their eye movements were continuously recorded using an eye-tracking system. However, because the present study focused on a single FCI item, the findings should be interpreted as describing visual attention during this specific problem-solving task rather than representing participants' problem-solvinf strategies across the entire FCI or other mechanics concepts. The FCI item used in this study is presented in Figure 1.

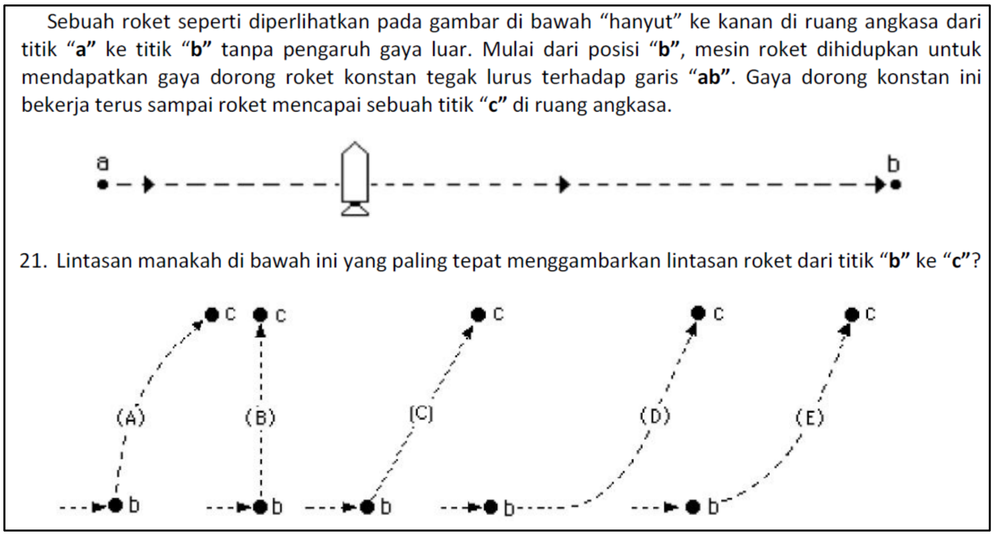

Figure 1. FCI Item Used.

Participants' eye movements were recorded using GazeRecorder, a webcam-based eye-tracking software that utilizes a computer's built-in camera without requiring specialized eye-tracking hardware (Bendjebar et al., 2026; García-Romero et al., 2025). GazeRecorder employs computer vision algorithms to detect facial features, eyes, irises, and gaze direction in real time (Falch & Lohan, 2024), enabling it to estimate participants' gaze positions on the computer screen throughout the problem-solving process. Before data collection, each participant completed a calibration procedure to ensure accurate recognition of individual eye characteristics and facial position.

2.4. Research Procedure

Before the study began, participants were informed about the research objectives and experimental procedures. Each participant was then seated approximately 40–50 cm from a computer screen under adequate lighting conditions. The laptop was positioned to ensure that the participant's face could be accurately detected by the built-in webcam. A calibration procedure was subsequently performed using GazeRecorder until the system achieved satisfactory tracking accuracy. After successful calibration, participants were instructed to complete one FCI item displayed on the computer screen within a time limit of 30 seconds. The predetermined duration was applied to provide a standardized observation period for all participants, allowing their vidual attention patterns to be recorded under equivalent temporal conditions. The use of a predetermined task duration is consistent with previous eye-tracking research in education problem-solving contexts, in which participants' eye movements are recorded while completing tasks within a defined observation period (Muna & Bahit, 2020)

2.5. Data Analysis

The eye-tracking data were analyzed descriptively using GazeRecorder. The analysis focused on three eye-tracking metrics: dwell time, gaze plot (scanpath), and heatmap, to identify participants' visual attention patterns while solving the FCI item. The analysis was conducted based on eight predefined Areas of Interest (AOIs) representing different components of the problem. These AOIs were defined according to the sections of the FCI item considered essential for conceptual reasoning, including the problem description, the rocket illustration, the main question, and each answer option. The definitions of the AOIs are presented in Table 1.

Tabel 1. Area of Interest (AOI)

AOI	AOI	Represented Physics Concept
AOI 1	Problem description	Initial motion without external force and the application of a constant perpendicular force (Newton's First and Second Laws).
AOI 2	Rocket illustration	Initial velocity vector and the direction of the applied force.
AOI 3	Question prompt	Identification of the rockey's trajectory from point b to point c.
AOI 4	Answer Option A	Alternative trajectory A.
AOI 5	Answer Option B	Alternative trajectory B.
AOI 6	Answer Option C	Alternative trajectory C.
AOI 7	Answer Option D	Alternative trajectory D.
AOI 8	Answer Option E	Alternative trajectory E.

3. RESULTS

This study employed a single FCI item to assess students' conceptual understanding of an object's motion under the influence of a constant force. The item required participants to integrate information from the problem statement, the accompanying illustration, and the answer options to determine the trajectory of a rocket after a thrust force was applied perpendicular to its initial direction of motion. According to Newton's First and Second Laws of Motion, the correct answer is Option E, which represents a curved trajectory resulting from the combined effects of the rocket's initial velocity and the continuous acceleration produced by the applied force.

Table 2 and Figure 2 show that participants devoted the greatest amount of visual attention to AOI 1, corresponding to the problem statement, with a mean dwell time of 9.40 seconds. This finding indicates that most participants spent a considerable amount of time processing the textual information before making a decision. After reading the problem statement, participants shifted their attention to AOI 2 (rocket illustration), with a mean dwell time of 4.72 seconds, followed by AOI 8 (Option E), with a mean dwell time of 4.12 seconds. In contrast, AOI 4 received very little visual attention, with a mean dwell time of only 0.07 seconds. This finding suggests that Option A was rarely considered during the problem-solving process.

All participants viewed AOIs 1, 2, 3, 6, 7, and 8, whereas AOI 5 was viewed by only eight participants. These results indicate that participants generally attended to the essential information presented in the problem before comparing the available answer options. However, the distribution of visual attention across the answer choices was not uniform, suggesting that participants selectively focused on certain alternatives while largely ignoring others.

Table 2. Descriptive Statistics of Eye-Tracking Metrics Across the Areas of Interest (AOIs).

AOI	Component	Mean Dwell Time (s)	Viewed by (%)
AOI 1	Problem Statement	9.4	100
AOI 2	Rocket Illustration	4.72	100
AOI 3	Question Statement	1.91	100
AOI 4	Option A	0.07	10
AOI 5	Option B	0.58	80
AOI 6	Option C	2.29	100
AOI 7	Option D	2.76	100
AOI 8	Option E	4.12	100

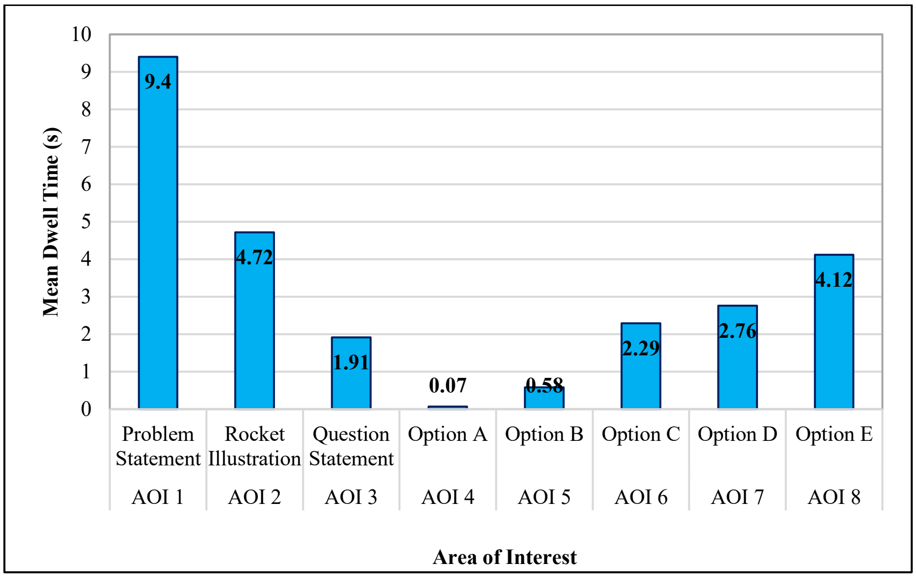

Figure 2. Distribution of Mean Dwell Time Across AOIs

Regarding participants' responses, five students (50%) selected Option E, which was the correct answer. Meanwhile, three students (30%) selected Option C, and two students (20%) selected Option D. None of the participants chose Option A or Option B. These results indicate that only half of the participants were able to correctly identify the rocket's trajectory based on the underlying physics concepts.

Figure 3 presents the distribution of dwell time for each participant across all Areas of Interest (AOIs) together with their selected answers. Darker color intensity represents longer dwell time within a particular AOI. Overall, all participants devoted substantial visual attention to AOI 1 (problem statement) and AOI 2 (rocket illustration), indicating that these areas served as the primary sources of information during problem solving. After processing the problem statement and illustration, participants shifted their attention to different answer options, exhibiting distinct visual attention patterns.

When examined alongside the eye-tracking data, participants' visual attention patterns varied according to their selected answers. Participants who correctly chose Option E (S1, S3, S7, S9, and S10) generally devoted relatively longer dwell times to AOI 8, corresponding to Option E. In contrast, participants who selected Option C (S2, S6, and S8) spent more time viewing AOI 6 than AOI 8. A similar pattern was observed among participants who selected Option D (S4 and S5), whose longest dwell times were concentrated on AOI 7. These findings suggest that participants tended to allocate greater visual attention to the answer option they ultimately selected. However, prolonged visual attention to a particular option did not necessarily reflect accurate conceptual understanding. Participants who selected Options C and D consistently focused on those alternatives, even though both responses were inconsistent with the correct physical interpretation of an object moving with an initial velocity while experiencing a constant force acting perpendicular to its direction of motion.

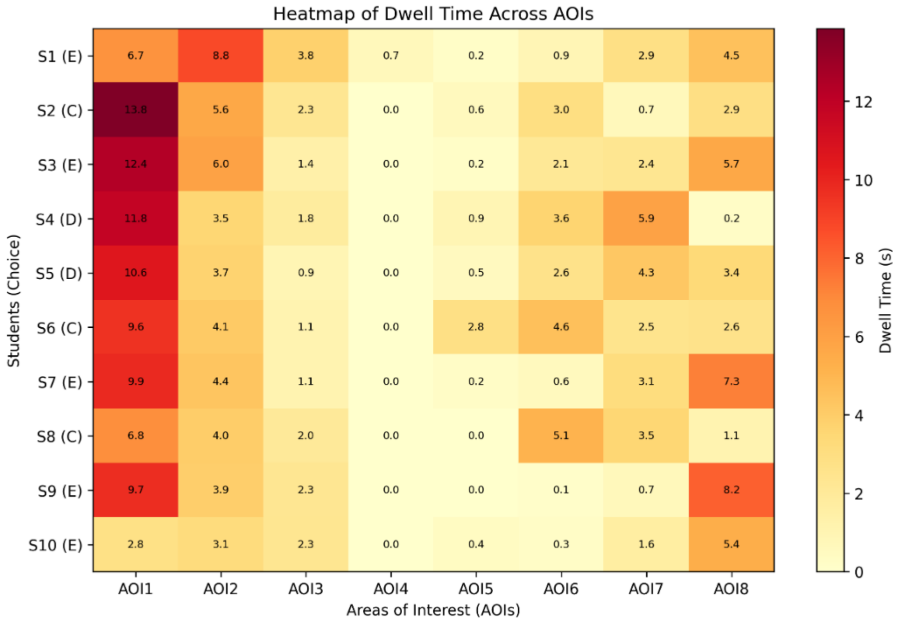

Figure 3. Heatmap Dwell Time per AOI

Figure 4 presents the heatmaps of participants' visual attention while solving the FCI item. Overall, the red and yellow regions, representing the highest levels of visual attention, were primarily concentrated on AOI 1 (problem statement) and AOI 2 (rocket illustration). This observation is consistent with the results presented in Table 2, which showed that these two AOIs had the highest mean dwell times. In addition, several participants exhibited substantial visual attention to AOI 8 (Option E), whereas AOI 4 received almost no visual attention across all heatmaps.

Despite these common patterns, considerable individual variation was observed. Participants who answered correctly generally displayed more focused visual attention on the problem statement, the rocket illustration, and Option E. In contrast, those who selected Option C or Option D showed more dispersed visual attention across multiple answer options before making their final decision.

Overall, the findings indicate that participants typically began the problem-solving process by concentrating on the key information presented in the problem statement and the accompanying illustration. Their visual attention then shifted toward the available answer options, particularly Option E, the correct answer. Nevertheless, the response distribution suggests that allocating substantial visual attention to the correct answer did not always lead to a correct decision. Several participants viewed the correct option but ultimately selected an incorrect alternative. These findings suggest that visual attention patterns provide valuable insights into students' conceptual problem-solving processes; however, successful performance ultimately depends on the quality of their conceptual understanding rather than visual attention alone.

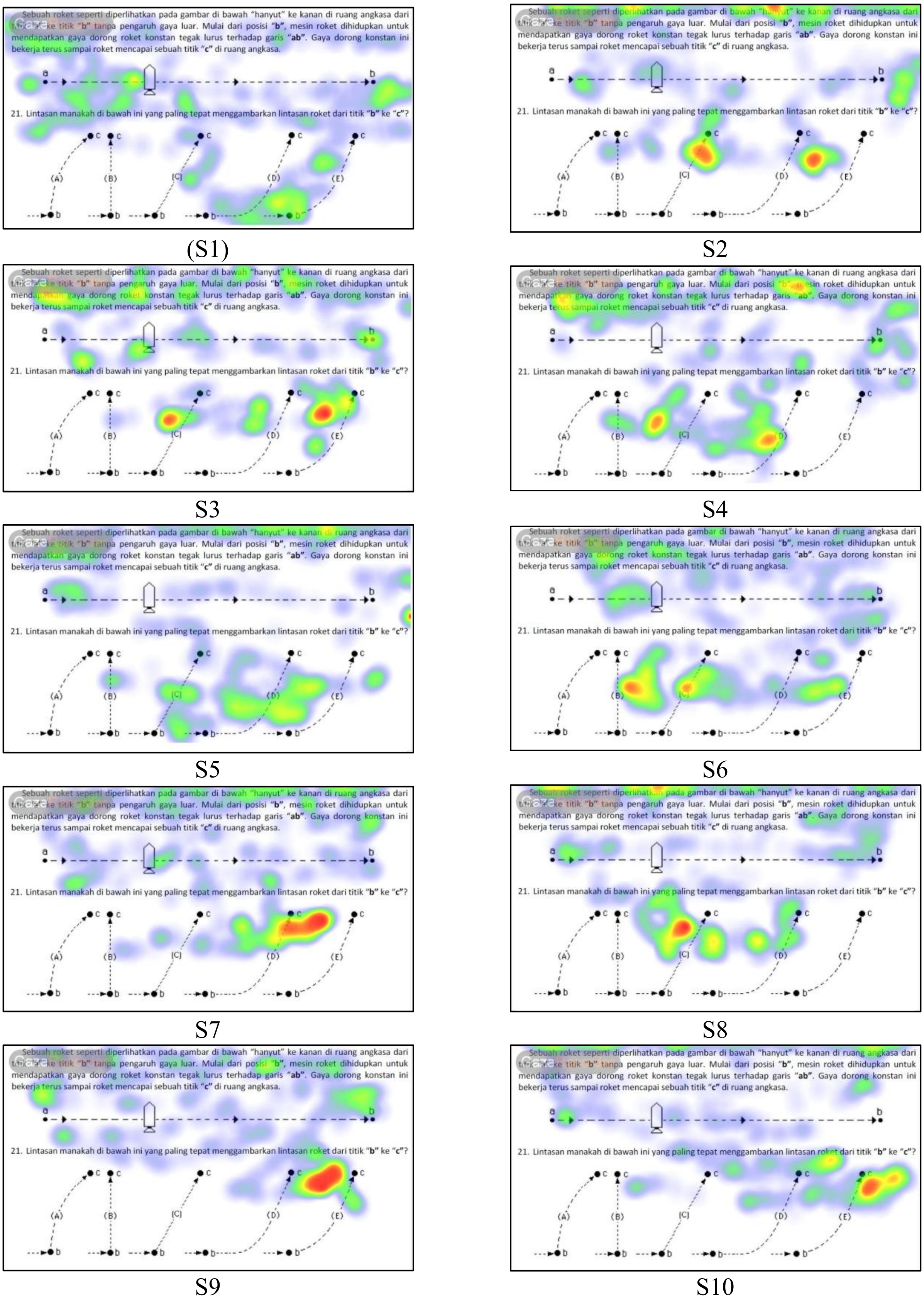

Figure 4. Heatmaps of Participants' Visual Attention from GazeRecorder

4. DISCUSSION

The findings indicate that participants devoted the greatest amount of visual attention to the problem statement (AOI 1) and the rocket illustration (AOI 2) before evaluating the answer options. This pattern suggests that participants first attempted to construct a mental representation of the physical situation before making a decision. From the perspective of Cognitive Load Theory, understanding the problem narrative and integrating visual information constitute essential initial stages for building conceptual schemas within working memory. Consequently, visual attention is naturally directed toward the primary sources of information before shifting to the available answer choices (Sevcenko et al., 2023; Q. Wang et al., 2014). Previous eye-tracking studies in educational settings have likewise shown that longer dwell times on relevant information generally reflect deeper cognitive processing, particularly during conceptual problem-solving task (Hao et al., 2025; Hu et al., 2017; X. Liu & Cui, 2025; Tóthová & Rusek, 2025)

However, extensive visual attention to the primary information did not necessarily result in correct answers. Only 50% of the participants selected Option E, whereas the remaining participants chose Option C or Option D. This finding indicates that visual attention to relevant information alone was not sufficient to ensure a correct response. Several participants attended to the problem statement and rocket illustration but ultimately selected an incorrect alternative. However, because the present study did not include interviews, think-aloud protocols, or other verbal data, the underlying reasoning processes and conceptual basis for these incorrect responses cannont be directly determined from the eye-tracking data alone. Therefore, the observed visual attention patterns should be interpreted as evidence of information allocation during problem solving rather than as direct evidence of participants' conceptual misconceptions. This interpretation is consistent with previous research suggesting that similar patterns of visual attention may be associated with different underlying cognitive processes and interpetations (J. Liu et al., 2026).

Further analysis revealed that participants who selected the correct answer generally devoted greater visual attention to AOI 8 (Option E), whereas those who selected Option C or Option D spent more time viewing the alternatives they ultimately chose. This pattern suggests that visual attention reflects not only information search but also the evaluation of answer options that participants perceive as being most consistent with their conceptual understanding. In eye-tracking research, dwell time is widely regarded as an indicator of information processing depth and cognitive resource allocation. Longer dwell times on a particular Area of Interest (AOI) indicate more intensive cognitive processing, although such processing does not necessarily lead to correct conclusions when the underlying conceptual framework is inaccurate.

The findings findings also demonstrate that visual attention directed toward Option E did not always result in its selection. Several participants allocated visual attention to the correct option before ultimately choosing Option C or Option D. This pattern suggests that exposure to or visual examination of the correct alternative alone was insufficient to predict the final response. In eye-tracking research, gaze measures provide evidence of where and for how long participants allocate visual attention, but they do not directly reveal the specific reasoning or interpretation underlying a decision (Helle, 2017; A. Wang & Pellicer-Sánchez, 2023). Therefore, although participants visually attended to Option E, the present data cannot determine whether they evaluated it as incorrect, compared it with other alternatives, or considered it before changing their decision. The discrepancy between visual attention and final response nevertheless highlights the value of combining eye-tracking data with complementary process measures when investigating conceptual problem solving. Previous methodological research has similarly emphasized that eye-tracking data can provide indirect evidence of cognitive processing, whereas verbal reports or retrospective interviews can offer additional information about the reasoning underlying observed gaze patterns.

From a methodological perspective, the present findings demonstrate the potential of webcam-based eye tracking as a practical tool for investigating students' thinking processes while solving conceptual physics problems. Unlike conventional assessments, which only distinguish between correct and incorrect responses, eye tracking provides valuable insights into how students allocate their visual attention throughout the decision-making process. Consequently, combining response accuracy with eye-tracking data offers a more comprehensive understanding of students' conceptual reasoning and enables instructors to identify potential misconceptions that may not be detected through test scores alone. These findings are consistent with recent developments in physics education research, where eye tracking has increasingly been adopted as a tool for diagnosing misconceptions and examining learners' problem-solving strategies (Becker et al., 2023; Tóthová & Rusek, 2025).

This study has several limitations. First, although the sample size was considered suitable for the exploratory and descriptive purpose of examining individual visual attention patterns, the relatively small number of participants limits the extent to which the findings can be generalized to a broader population. Second, the study examined only a single Force Concept Inventory (FCI) item; therefore, the observed visual attention patterns should be interpreted in relation to this specific problem and may not represent participants' strategies across other mechanics concepts. Third, the study employed GazeRecorder, a webcam-based eye-tracking system that provides a practical and accessible alternative to dedicated infrared eye trackers. However, webcam-based gaze estimation generally offers lower spatial accuracy and is more sensitive to variations in participant position and recording conditions than specialized infrared eye-tracking systems (Falch & Lohan, 2024). Therefore, the precision of the recorded gaze positions should be considered when interpreting the observed visual attention patterns.

Future research should involve larger and more diverse participant samples, incorporate multiple FCI items representing a wider range of mechanics concepts, and compare visual attention patterns across learners with different levels of conceptual understanding. In addition, integrating eye-tracking data with complementary approaches, such as confidence ratings, think-aloud protocols, or eye-tracking-based misconception diagnosis models, may provide a more comprehensive understanding of students' cognitive processes while solving conceptual physics problems.

5. CONCLUSION

This study demonstrates that eye-tracking analysis provides deeper insights into students' conceptual problem-solving processes in physics than relying solely on their final answers. The observed visual attention patterns reveal how preservice physics teachers process information, evaluate alternative answers, and make decisions while completing a Force Concept Inventory (FCI) item. These findings highlight the potential of eye tracking as a complementary tool for diagnostic assessment, enabling researchers and educators to identify students' thinking patterns and potential misconceptions that may not be detected through conventional assessments. Therefore, integrating eye-tracking technology into physics education research and assessment represents a promising approach for supporting the development of more effective, evidence-based instructional strategies.

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