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Analysis of Misconceptions among Physics Education Students on Special Relativity Theory

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ABSTRACT

This study explores persistent misconceptions among students in physics education programs regarding the Special Theory of Relativity. Despite formal instruction, many still show fragmented understanding, often reverting to classical concepts. The aim is to identify dominant misconceptions and analyze cognitive and pedagogical causes. Using a qualitative descriptive method, 25 fifth-semester physics education students from a public university in Indonesia participated. Data were collected through a validated 20-item multiple-choice diagnostic test and semi-structured interviews. Analysis involved data reduction, narrative development, and expert triangulation. Results show frequent misconceptions in time dilation (72%), length contraction (64%), and simultaneity (60%). Students misinterpret time dilation as an absolute change, view length contraction as permanent, and fail to understand simultaneity's relativity. Contributing factors include limited visual aids, inadequate contextual teaching, and lack of engaging media. To address this, the study suggests using digital tools like simulations and animations and adopting constructivist-based strategies. These are expected to deepen understanding and correct misconceptions. The findings aim to enhance modern physics teaching at the tertiary level.

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A. INTRODUCTION

The special theory of relativity, introduced by Albert Einstein in 1905, represents a profound transformation in the field of physics, redefining fundamental notions of space, time, and motion (Müller & Schäfer, 2021). While it stands as a cornerstone of modern scientific thought, the theory's abstract and counterintuitive nature presents significant challenges for learners, particularly those transitioning from the deterministic framework of classical mechanics (Kurniawan et al., 2023; Leonardi et al., 2024).

Recent research has underscored that misconceptions about Special Relativity persist even after formal instruction, suggesting that conventional teaching methods often fail to instill a deep conceptual shift from Newtonian to relativistic thinking (Leonardi et al., 2024; Acuña, 2016). These misconceptions are not merely due to lack of content knowledge, but stem from cognitive dissonance between intuitive, everyday experience and the counterintuitive principles of relativity (Hughes & Kersting, 2021; Korkmaz et al., 2016). Learners commonly conflate visual and coordinate time, misinterpret the constancy of the speed of light, and misapply simultaneity, all of which contribute to fragmented understanding (Hughes & Kersting, 2021).

Scholars have emphasized the need for pedagogical innovations, including the use of analogical reasoning, guided inquiry, and interactive simulations to overcome these obstacles (Korkmaz et al., 2016; Leonardi et al., 2024). Visual aids such as world diagrams and event maps, paired with diagnostic assessments, have been effective in illuminating the abstract dynamics of relativistic transformations (Hughes & Kersting, 2021). Moreover, metacognitive strategies and conceptual change models are being increasingly adopted to foster durable understanding among students.

Despite these advancements, misconceptions remain prevalent among students of physics education. This indicates that existing teaching approaches do not fully resolve the conceptual conflicts students face. If these misconceptions persist, the development of critical scientific reasoning in modern physics will be hindered. The urgency of this study stems from the pressing need to design teaching strategies that directly confront these misconceptions (Marisda et al., 2025), thereby enabling meaningful conceptual change and improving the quality of physics education in higher education (Marisda et al., 2023).

Previous studies have examined different interventions, including analogical reasoning (Korkmaz et al., 2016), conceptual conflict models (Yuliana & Hidayat, 2022), interactive simulations (Zakwandi & Jumadi, 2021), and diagnostic tests (Çelikkanlı & Kızılcık, 2022). Valuable insights have been provided by these works into both the persistence of misconceptions and possible pathways for remediation. However, most of these studies tend to examine either diagnostic aspects or the application of specific teaching interventions in isolation. Comprehensive research that explicitly integrates both the diagnosis of misconceptions and the pedagogical responses remains limited.

The main gap identified is the lack of research that connects the process of assessing a student's needs with new teaching methods in a planned way. While prior studies have highlighted misconceptions and tested the effectiveness of teaching methods, they often fail to connect these processes within a holistic framework. This study's novel approach combines validated diagnostic instruments with qualitative interviews to identify misconceptions, analyze their cognitive and pedagogical roots, and propose adaptive instructional designs. This integrative approach is expected to provide a more complete understanding of how misconceptions form and persist while offering practical strategies to address them.

This study offers evidence-based recommendations that map out the dominant misconceptions in special relativity and identify the pedagogical shortcomings that perpetuate them. Unlike previous research, which tends to separate assessment and intervention, this study proposes a framework that links the two. Through this approach, the study aims to improve the design of modern physics instruction, encourage deeper conceptual change, and foster a coherent understanding of relativistic principles among students of physics education.

B. RESEARCH METHOD

This study employed a qualitative approach with a descriptive design to identify and analyze misconceptions held by physics education students in understanding the topic of special relativity. The research subjects consisted of 30 fifth-semester students from the Physics Education Study Program at a public university in Indonesia. Participants were selected purposively based on the criterion that they had completed a course in Modern Physics.

Data collection involved two main instruments. The first was a diagnostic test comprising 20 multiple-choice questions that had been validated by experts and specifically designed to detect misconceptions in three core concepts of special relativity: time dilation, length contraction, and simultaneity. The second instrument was a semi-structured interview conducted with 10 students selected based on their diagnostic test results. The interviews aimed to explore the underlying reasons behind the misconceptions in greater depth.

The data analysis process consisted of three stages: data reduction, data presentation, and verification. During the reduction phase, data from both the test and interviews were filtered to focus on the most prominent misconceptions. Data presentation was conducted narratively and supported by direct quotations from the interviews to reinforce the findings. Verification was carried out by comparing results from both instruments and through discussions with experts in physics education to ensure the validity of the findings.

Ethical considerations were carefully observed by maintaining the confidentiality of all participants and obtaining written consent prior to data collection. All procedures adhered to the ethical standards applicable in academic research environments.

C. RESULTS AND DISCUSSION

1. General Description of Findings

Before presenting the results and discussion, it is important to provide an overview of the findings that emerged from the data collection process. The analysis focuses on identifying the dominant misconceptions held by physics education students regarding key concepts in Special Relativity. Through a combination of a validated diagnostic test and follow-up semi-structured interviews, this study sheds light on the specific areas where students struggle most, such as time dilation, length contraction, and simultaneity. These misconceptions are explored not only in terms of their prevalence but also in relation to the cognitive and pedagogical factors that contribute to their persistence. The subsequent sections will present the data in detail, followed by an in-depth discussion of the implications of these findings for teaching and learning in modern physics education.

This study involved 25 students from the Physics Education Study Program who had completed the Modern Physics course. The instruments used included a 20-item multiple-choice diagnostic test designed to detect misconceptions, as well as semi-structured interviews intended to explore the origins of these misconceptions in greater depth.

Table 1. Misconception Distribution by Concept

Concept	Number of Students	Percentage	Related Items
Time Dilation	18	72%	1, 7, 8
Length Contraction	16	64%	2, 9, 16
Simultaneity	15	60%	3, 13, 17
Relativistic Mass	12	48%	4, 10, 19
Speed of Light	14	56%	5, 6, 15
Inertial Frame Application	11	44%	11, 12, 14, 18, 20

2. Expanded Analysis and Discussion

The analysis of misconceptions among physics education students regarding Special Relativity Theory reveals a multifaceted challenge rooted in the inherent abstraction of the theory. One prominent finding is that students frequently conflate what is observable with what is measured, a confusion that particularly affects their understanding of phenomena such as time dilation and length contraction (Hughes & Kersting, 2021). These misconceptions persist because relativistic effects are non-intuitive and often “invisible” without proper visualization tools, leading students to default to everyday experiences rather than the counterintuitive predictions of the theory (Hughes & Kersting, 2021).

This study found that 72% of participants held misconceptions about time dilation and 64% about length contraction. These findings align with Leonardi et al. (2024), who reported that many students misapply classical frameworks when reasoning about relativistic effects. Structured diagnostic tests reveal that these misunderstandings are systematic, stemming from reliance on intuitive, non-scientific reasoning and confusion between visual and measured phenomena.

The interviews revealed notable differences among students in how they reasoned about relativistic concepts. Some students struggled primarily due to reliance on everyday experiences (e.g., assuming simultaneity is absolute), while others were hindered by a lack of visualization tools, which made it difficult to conceptualize abstract ideas such as length contraction. A smaller group demonstrated partial understanding but misapplied mathematical formalism, indicating that gaps in connecting formal equations to physical meaning also contributed to misconceptions. These variations highlight that not all misconceptions arise from the same root causes; rather, they emerge from a combination of cognitive habits, instructional shortcomings, and limited exposure to interactive or contextualized learning media.

Educational approaches also play a key role. Kamphorst et al. (2021) emphasized that the conventional narrative of Einstein’s thought experiments, without sufficient engagement in theoretical discourse or empirical exploration, impedes conceptual understanding. Likewise, Çelikkanlı & Kızılcık (2022) advocate for the use of four-tier diagnostic tests to identify and confront these embedded misconceptions effectively.

Further complicating the learning process is the disconnection between mathematical formalism and conceptual intuition. Liu (2024) notes that abstract representations of the spacetime continuum, while mathematically necessary, can obscure understanding unless deliberately bridged with empirical and intuitive frameworks.

The qualitative portion of this study reinforces these insights. Interview findings demonstrated three main sources of variation in misconceptions among students: Everyday experience bias, leading to reliance on classical reasoning; Instructional gaps, such as minimal use of simulations, diagrams, or interactive media; Cognitive and formalism challenges, where some students understood equations but misinterpreted their conceptual meaning.

For instance, students often believed that simultaneity is absolute, suggesting limited understanding of relativistic reference frames. Supporting this, Hughes & Kersting (2021) observed that students' narrative mental models, derived from intuitive experiences, conflict with scientific interpretations. Kamphorst et al. (2021) and Fadillah et al. (2024) further reveal that students who engage in guided narrative reflection or AI-powered exploratory dialogue, such as through tools like ChatGPT, are better able to articulate and reshape their misconceptions.

Kahaleh & López (2025) highlight that AI-mediated learning environments not only expose cognitive but also emotional responses, offering holistic insights into student learning. This narrative- and technology-driven approach opens new pedagogical opportunities.

Taken together, these findings affirm that misconceptions in Special Relativity are not only measurable and significant (Leonardi et al., 2024), but also cognitively and emotionally embedded, with meaningful differences across students that must be acknowledged in instructional design.

D. CONCLUSION

This research highlights the continued presence of conceptual misunderstandings among students in Physics Education Study Program, particularly in relation to core topics within Special Relativity. Areas such as time dilation (72%), length contraction (64%), and simultaneity (60%) were found to be the most frequent misconceptions, while additional difficulties also emerged regarding relativistic mass (48%), the constancy of light speed (56%), and applications of inertial frames (44%). These results are consistent with the diagnostic test outcomes presented in the abstract, which indicated that students tend to interpret time dilation as an absolute change, view length contraction as a permanent effect, and fail to understand the relativity of simultaneity.

Findings from follow-up interviews further reveal that these misconceptions are primarily rooted in everyday reasoning patterns, limited access to visual and simulation-based instructional tools, and teaching strategies that fail to effectively engage students in cognitive conflict. These contributing factors confirm that the persistence of misconceptions is not merely a content-related issue but also pedagogical and cognitive in nature.

The implications of this study emphasize the need to reformulate how Modern Physics, particularly Special Relativity, is taught. To effectively address these conceptual barriers, educators must adopt a multifaceted instructional approach that integrates digital tools such as simulations and animations, applies advanced diagnostic assessments like four-tier tests, and incorporates constructivist-based strategies. Equally important is bridging abstract mathematical formalism with tangible physical intuition to reinforce student comprehension.

The broader implications of this study suggest meaningful pathways for improving instructional design in higher education physics courses. By embracing evidence-based pedagogical innovations that respond to both cognitive and emotional dimensions of learning, educators can more effectively guide students toward a robust and accurate understanding of Special Relativity.

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