

Undergraduate students' application of special relativity to paradoxes

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In this paper, the focus has been on students' application of special relativity theory after learning it. In order to determine students' understanding and conceptualization of the theory of special relativity, paradoxes, which are contradictory problems, have been used in the study. How students solved paradoxes related to the relativity of simultaneity, length contraction, and time dilation has been investigated, and an answer has been sought to the question "What is the state of undergraduate students who have learnt special relativity theory in applying the theory to paradoxes?" The students who participated in the study had previously attended Physics I, General Physics 2, and General Physics 3 courses in which classical physics topics (force and motion, electricity and magnetism, and optics and waves) were taught. The data were analyzed using a phenomenographic approach to identify the categories emerging from students' responses. Most students experience difficulty in understanding the nature of special relativity and applying the theory to other situations. For this reason, they did not use the concept of the reference frame in solving the paradoxes. From the students' responses, it is understood that they mostly think within a single reference frame and experience difficulty in understanding the contradictions that arise when viewed from different reference frames.

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I. INTRODUCTION

Modern and contemporary physics play a crucial role in the emergence of technological resources that are renewed daily in the developing world [1,2]. The incorporation of theories from modern and contemporary physics into fundamental physics education in schools is of great importance for the development of individuals' scientific literacy and their preparation for a technologically advancing world [3]. However, examination of physics education curricula reveals that, despite the inclusion of modern and contemporary physics topics, many classroom practices still focus on classical physics, and the importance of modern and contemporary physics is largely overlooked [4]. Individuals typically attempt to explain phenomena encountered in their daily lives through classical physics knowledge acquired via observation. Relativity theory, one of the foundations of modern and contemporary physics, is unconventional and distinct for individuals. Consequently, many situations that individuals encounter in their lives appear to contradict the relativity theory. Relativity theory reveals that certain assumptions individuals consider valid

and do not question are, in fact, invalid. The most fundamental difficulty faced by individuals beginning to learn this theory is distinguishing which assumptions are valid and which are invalid.

We can rephrase these assumptions of Einstein as follows:

1. The laws of physics are the same in all inertial systems. No preferred inertial system exists
2. The speed of light in free space has the same value c in all inertial systems. [5]

The laws of physics are invariant in all inertial reference frames (nonaccelerating). This assumption is known as the first postulate of special relativity theory. The concepts of time and space are fundamental to this postulate of special relativity theory. The relative nature of space and time can be comprehended not through sensible experiments as in classical physics but through the correct perception of the concepts of the special relativity principle [6]. The literature contains numerous studies examining students' conceptions regarding the concept of time in special relativity [7–11]. These studies demonstrate that students at all levels struggle to articulate the relativity of simultaneity and the role of the observer in inertial reference frames [7].

Students tend to believe that simultaneity is independent of absolute and relative motions [10,12]. Similarly, students have expressed that absolute simultaneity and the relativity of simultaneity are compatible [10]. Students

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struggle to understand the concept of reference frames. Two events occurring simultaneously at different locations in a particular reference frame are not simultaneous in all other reference frames [6]. Scherr *et al.* [13] developed instructional materials to enable students to understand the role of observers in inertial reference frames. With these materials, they aimed to enable students to correctly articulate the concept of “same time” and the “relativity of simultaneity.” As a result of interviews conducted with students, they determined that students’ beliefs regarding the concept of simultaneity were inconsistent with the consequences of special relativity theory. They concluded that students exhibited intense cognitive conflict as a result of confronting this misconception. When individuals describe events related to special relativity theory, they confuse the moment an event occurs with the moment it is perceived by the observer [10,14]. One of the most fundamental reasons for this is their failure to define and use the concept of “event” [15].

In their study examining the reasoning of prospective physics teachers related to the concepts of reference frame, time, and event, de Hosson *et al.* [6] determined that neither the concept of reference frame nor the concept of event was deeply understood. Some students believe that events occurring in the same reference frame may be simultaneous for one observer, while not being simultaneous for another. Most students participating in the study are unable to provide an answer dependent on the observer’s position when the observer’s velocity is mentioned.

Selçuk [11] investigated prospective teachers’ understanding of the concepts of time, length, mass, and density in special relativity theory and their difficulties with these concepts. The study demonstrates that prospective teachers at different academic levels experience specific and significant difficulties with the concepts of proper time, time dilation, proper length, mass, and relativistic density.

The second fundamental postulate of special relativity theory is the constancy of the speed of light. The speed of light in a vacuum is not affected by the motion of the observer or the light source and is the same for all observers. Students fail to recognize the invariance of the speed of light. They believe that the speed of light is a constant value, yet they may think that observers measure this value differently in different observational frames [12]. They believe that the “true” speed of light can only be observed in the “rest frame” of the light source. From this, students believe that velocity is an absolute concept. In their study analyzing postgraduate students’ ideas regarding the speed of light, Villani and Pacca [12] stated that students believed time dilation and length contraction occur only for a moving observer.

A cognitive framework consisting of Newtonian mechanics is taught to children from secondary education onward as a problem-solving, unproblematic, and robust

science, even though we know it to be entirely incorrect [16]. The idea of absolute motion in classical mechanics becomes firmly embedded in students’ ways of thinking about physics from secondary education onward [17]. Teaching the ideas of 20th-century special relativity, subsequently, in this manner makes the learning of modern physics extremely difficult [16]. For special relativity to be comprehended, the commonly taught form of classical mechanics must be modified for students, and it is important to always liberate students from the idea of an absolute reference frame [12,17]. This situation means that students experience a major change in the conceptual framework they have constructed in their minds thus far. This change in the conceptual framework requires fundamental knowledge accumulation regarding basic phenomena such as reference frame, event, space, time, and the speed of light. In special relativity, an event is defined as a phenomenon occurring at a specific location in space and at a specific instant in time. Two events at different locations occurring simultaneously in a particular reference frame are not simultaneous in other reference frames. This situation is expressed as simultaneity not being absolute, unlike in Newtonian mechanics. Multiple observers at rest relative to one another can exist in a reference frame. These observers attempt to determine the distances and time delays between a series of events. In the transition from Newtonian mechanics to 21st-century modern physics theories, students should acquire qualitative reasoning practice by discussing the causal ordering of events rather than performing quantitative calculations, in order to facilitate their understanding of all these concepts [13].

To meet this need, various thought experiments that appear to contain contradictions are used [18]. As the name suggests, in these experiments, which are designed only in thought and can never actually be performed, the results to be obtained are sought through two different methods. However, both methods predict results that contradict one another. After the student is enabled to see the contradiction, it is demonstrated that one of these methods has been applied incorrectly and employs an assumption that should not be made [19]. Paradoxes are one such type of thought experiment [18].

A. Purpose

Students’ learning levels regarding a topic can be determined by their ability to apply knowledge to different situations. The two fundamental postulates of the special relativity principle are the principle of relativity and the invariance of the speed of light. Therefore, students’ application of the theory’s fundamental postulates to problems they encounter and the extent to which they can apply them serve as important indicators of their learning levels. This paper focuses on students’ application of special relativity theory after learning it. Paradoxes,

which are contradictory problems, were used in the study to determine students' understanding and conceptualization of the theory of special relativity. The study investigated how students resolved paradoxes related to the relativity of simultaneity, length contraction, and time dilation, seeking to answer the research question: "What is the state of undergraduate students' application of special relativity theory to paradoxes after learning the theory?"

II. METHODS

A. Research model

This study examined undergraduate students' application of the fundamental postulates of special relativity theory to problems they encounter. A case study design, one of the qualitative research methods, was used in the research. In qualitative case studies, the researcher aims to examine and describe one or several cases in depth [20]. Studies in which a single unit or case is examined in depth are referred to as holistic single-case designs [21]. As this study aimed to reveal in detail how students apply special relativity theory to paradoxes they encounter, a holistic single-case design was adopted.

B. Sample

The study group consisted of 48 undergraduate students enrolled in the second year of a science teacher education program at a state university in central Turkey, who participated voluntarily in the study. Purposive sampling, in which researchers determine and select the characteristics of individuals who will constitute the research population, was used in the study [22]. The students participating in the study had previously attended Physics I, General Physics II, and General Physics III courses, which covered classical physics topics (force and motion, electricity and magnetism, and optics and waves). Students who had completed these courses and were enrolled in the modern physics course were selected as participants for the research. The study was conducted with second-year undergraduate students at the university where the first author teaches, within the scope of the author's course.

During the course, special relativity theory was taught to prospective teachers over 6 weeks, including its historical development and philosophical aspects. Numerical calculations were not included. Initially, the relative velocities of a car and a lorry, followed by a rocket and a beam of light passing alongside it, were presented using examples of relative motion. Students were informed about the problem that the constancy of the speed of light created for scientists. The Earth's motion, the constancy of the speed of light, and Galileo's observation that the Earth's motion has no effect on our lives were addressed. Subsequently, inertial reference frames, the fact that different

observers perceive space and time differently, and that relativity theory examines the relationship between space and time according to different observers were discussed. Five fundamental consequences of relativity theory were explained to students. It was stated that all motions are relative, that a clock in a moving system operates differently from one in a stationary system, and similarly that the length of an object in a moving system can vary according to the system's velocity; thus, an introduction to the Lorentz transformation equations was provided. In this section, only five equations were presented individually with explanations. The derivations of the equations were not included. Length contraction, time dilation, mass increase (relativistic mass), relative velocity, and mass-energy equivalence were explained in detail, and these changes were demonstrated to students through simple mathematical operations. At the end of the lessons, students learned about special relativity theory and its applications from the perspective of an observer. Following the instruction in special relativity theory, the study investigated students' application of this theory. In this context, open-ended questions regarding paradoxes, one of the application areas of special relativity theory, were used as data collection instruments in the research. Students participating in the study were expected to read the paradoxes and solve them using the postulates of special relativity theory. Four paradoxes related to time dilation, length contraction, simultaneity, and causality were selected for the study. In selecting these paradoxes, the twin paradox, the pole-barn paradox, the train-lightning paradox, and the grandfather paradox were chosen, as they both appear in modern physics textbooks and are popular in general knowledge. Only the paradoxes were presented in the data collection instrument, and students were asked to explain how they would resolve these paradoxes. The data collection instrument used in the research is appended. Participants were given 60 min to complete the data collection instrument. Participants were assured that the information would not be shared with anyone under any circumstances and that they were not required to write their names. This research was approved by the ethics committee of the university with which the authors are affiliated.

C. Data analysis

The data were analyzed using a phenomenographic approach to identify the categories emerging from students' responses. This approach seeks to reveal the different ways in which individuals conceptualize the same phenomenon and how they structure their understanding of it [23,24]. Within phenomenography, concepts and modes of understanding are not treated as individual attributes; rather, they are regarded as descriptive categories that group the ways in which individuals make sense of situations [25]. These categories are considered stable

insofar as, notwithstanding the possibility of individuals moving from one category to another over time, they tend to emerge in comparable forms across different contexts and among different individuals. In this regard, phenomenography enables researchers to move beyond individual experience and illuminate a collective mode of understanding that is subsumed under the same descriptive category [24,26].

The data were collected in Turkish, which is the native language of both the authors and the participants, and the data analysis was likewise conducted in Turkish. During the initial phase of data analysis, the responses of 48 students were examined independently by each author, and descriptive categories were constructed for each question. The authors subsequently convened as an expert group to evaluate the emerging categories and to reach a consensus. The descriptive categories were developed on the basis of the students' own explanations. Given the inherently paradoxical nature of the items, each paradox encompasses two distinct solutions corresponding to two different frames of reference; nevertheless, these solutions converge upon a single correct outcome. Furthermore, each paradox is resolved by drawing upon a different postulate of the special theory of relativity. Owing to these structural characteristics of the paradoxes, distinct descriptive categories were constructed for each question. All responses were analyzed systematically, whereupon the properties of the emerging categories were identified and classified. In instances where new categories arose from the data during the expert group evaluation process, these were incorporated into the analysis through an iterative procedure. The phenomenographic hierarchy is based not on the degree of correctness of students' responses but rather on the extent to which the critical aspects of a given phenomenon are discerned and the manner in which the relationships among these aspects are constructed [23]. Accordingly, the descriptive categories generated during the analysis process possess a hierarchical structure; however, this structure is not used to determine whether a given response is correct or incorrect. Instead, the categories serve to describe the extent to which students are able to shift between different frames of observation in their responses, the conceptual difficulties and learning challenges they encounter in transitioning from classical to modern physics, and the forms of reasoning they employ in order to arrive at a single correct conclusion in dilemmatic questions. The process of constructing and validating the descriptive categories was carried out by subject-matter experts, and the determination of the hierarchy of descriptive categories was likewise grounded in expert evaluations.

The paradoxes used in this study are designed to elicit students' conceptual understanding of the special theory of relativity, particularly with respect to fundamental concepts such as the choice of reference frame, length

contraction, time dilation, the relativity of simultaneity, causality, and temporal ordering. Rather than assessing students' mathematical knowledge, the paradoxes take the form of thought experiments intended to evaluate how students interpret physical situations and the extent to which they are able to shift between different observational perspectives.

In the analysis of the paradoxes, particular attention was paid to the ways in which students applied the principles of relativity in their responses, as well as to their erroneous or incomplete causal explanations, their reliance on classical physics assumptions, their contradictory answers, the manner in which they established cause-and-effect relationships, and the strategies they adopted with respect to temporal ordering. More specifically, in the context of the pole-barn and train paradoxes, the analysis examined whether students treated the concept of simultaneity as absolute or relative; in the twin paradox, whether they recognized the role of accelerated motion; and in the grandfather paradox, how they interpreted the principle of causality. Within this framework, the paradoxes were regarded as diagnostic instruments capable of revealing students' levels of conceptual understanding, and the responses were classified according to the degree of their consistency with the fundamental principles of the theory of relativity.

In constructing these classifications, the categories obtained through the phenomenographic analysis were combined with hierarchical themes. Categories comprising responses in which the fundamental principles of the theory of relativity (e.g., simultaneity, reference frame, and the invariance of the speed of light) were applied correctly and consistently within a single coherent observational frame of reference were brought together to form the hierarchy of "Holistic and Consistent Application of Relativistic Principles." Categories consisting of responses in which concepts related to the theory of relativity were applied, but which contained erroneous, incomplete, or contradictory inferences with respect to the reference frame, simultaneity, or physical constraints, were consolidated to form the hierarchy of "partial or inconsistent application of relativistic principles." Categories comprising responses that involved no application of the principles of relativity but instead relied upon classical physics assumptions, intuitive cause-and-effect reasoning, or explanations grounded in everyday experience were grouped to constitute the hierarchy of "classical or intuitive reasoning-based explanations." Categories consisting of responses that students had left blank or in which no conceptual justification was provided were combined to form the hierarchy of "responses lacking explanation." It should be noted that the categories brought together in constructing these hierarchical themes do not themselves possess a hierarchical structure. For instance, students were unable to draw upon more than one reference frame

in resolving the paradoxes, instead formulating their responses by adhering to a single reference frame. Consequently, the theme of “holistic or consistent application of the theory of relativity” comprises categories that are not hierarchically ordered but are each constructed from responses provided within a particular observational frame of reference.

D. Reliability

To ensure the reliability of data obtained from explanations of solutions to open-ended questions, all responses to the questions were analyzed individually by two different physics education experts. Subsequently, the analyses of the two experts were compared, and the agreement (consistency) percentage was calculated as 95% [27]. Differences were discussed, and the analysis was revisited for codes on which a decision could not be reached. The analysis was completed upon reaching consensus between the two researchers. To ensure the external validity of the paradoxes included in the data collection instrument in the study, they were selected and implemented by the researchers after obtaining expert opinion. Furthermore, the research process was expressed to participants as clearly and explicitly as possible. To ensure internal reliability, direct examples from the explanations students used in solving the paradoxes are provided. In this study, to ensure validity, expert opinion was obtained at every stage of the research, and a detailed analysis was attempted.

III. RESULTS

As a result of the analysis, the ways in which students utilized the special theory of relativity in resolving the paradoxes were categorized under four hierarchical themes. These themes demonstrate a conceptual shift, ranging from the holistic application of relativistic principles to explanations based on classical physics or intuitive reasoning and responses lacking any explanation. This process of conceptual transition is examined in detail in this section, with each paradox addressed individually.

A. Students' understanding of the pole-barn paradox

The categories derived from the analysis of students' responses to the pole-barn paradox are presented in Table I.

The analysis reveals that theme A comprises responses from category A1 alone. It was determined that 33.3% of students used Lorentz contraction and a single reference frame in which the barn is stationary and the pole is in motion. An illustrative example of this category is provided by S12's response: “When both objects are at rest, they are of equal length, and the pole fits exactly inside the barn and the door closes. If the pole is launched at a velocity approaching the speed of light, its length contracts. It would fit comfortably within the space inside

the barn; there would, in fact, be empty space remaining. That is, as the pole approaches the speed of light, its length decreases.”

An examination of students' responses within theme B reveals that 18.7% produced responses falling within category B3 by misapplying Lorentz contraction. S38's response, “If we consider the pole being launched into the barn at high speed, we cannot place the pole inside and close the door. Since the pole is moving at a velocity close to the speed of light, its length will expand and it will not fit inside the barn,” may be cited as an example of this category. It is observed that 35.4% of all student responses were grouped under this theme. Among the remaining categories within this theme, S14's response, “We can close it. We could not close it only if the speed of the pole exceeded the speed of light,” exemplifies category B1. Category B2 is illustrated by S4's response: “If the pole is launched at a velocity close to the speed of light while the barn is stationary, we cannot close the barn door. Because in order to close the barn door, we would need to be moving at a speed greater than or equal to that of the pole. Since we can never attain such a speed, this would not be possible.” S5's response, “Yes, we can close it. Because although the length of the pole may appear to change from our perspective, it does not actually change, and we can place it inside and close the door,” serves as an example of category B4.

It is noteworthy that 25.1% of students' responses incorporated a range of concepts such as absolute length, the action-reaction principle, and momentum and were grouped under the theme of classical or intuitive reasoning-based explanations. Representative examples from this theme are as follows:

From category C1, S9's response: “If the pole is launched into the barn at a velocity close to the speed of light, the pole will shatter and break.”

From category C2, S26's response: “No, we cannot place it inside; the pole will pass straight through the barn and keep going. Because the speed of light is the fastest thing in the world.”

From category C3, S21's response: “We cannot close it. It will not fit. Stretching will occur and the pole will become larger than the barn.”

From category C4, S8's response: “Regardless of the speed of the pole, its actual length will not change, so the pole will fit inside the barn and the door will close.”

From category C5, S22's response: “If we bring the barn to the same speed as the pole, then we can place the pole inside and close the door.”

From category C6, S34's response: “We cannot close it. The pole will come in at speed, strike the barn, and move in the direction opposite to the one from which it came.”

From category C7, S41's response: “In this case, we cannot close the barn door. If the pole is pushed into

TABLE I. Students' responses to the pole-barn paradox.

Theme	Category	Definition of the category	Description of the category	%
A—Holistic or consistent application of relativistic principles	A1—Lorentz contraction within a single frame of observation	Explanations that acknowledge Lorentz contraction but are based on a single reference frame	States that the pole shortens at velocities approaching the speed of light; employs the frame in which the barn is stationary and the pole is in motion	33.3
	B1—Neglect of physical limits	Explanations that acknowledge length contraction but assume that the speed of light can be reached	Accepts relativity yet disregards the speed of light as an upper limit	10.4
B—Partial or inconsistent application of relativistic principles	B2—Inconsistency with physical limits	Explanations that acknowledge length contraction but assume that the observer cannot reach the speed of light	Accepts relativity yet states that the speed of light constitutes an upper limit that cannot be attained	2.2
	B3—Superficial or erroneous application of Lorentz contraction	Explanations that interpret Lorentz contraction in an incorrect, incomplete, or contradictory manner	Applies length contraction in the wrong direction, in an exaggerated form, or in a manner disconnected from context	18.7
	B4—Intuition-based application	Explanations of relativity grounded in everyday perception	Employs intuitive expressions such as “as we see it” or “normally”	4.1
	C1—Identification of velocity with force	Explanations that treat velocity as a destructive or disruptive effect	Interprets velocity as equivalent to force or destruction	4.1
C—Classical or intuitive reasoning-based explanations	C2—Velocity as an absolute and unstoppable effect	Explanations that regard velocity as an unstoppable effect	Assumes that the pole will continue moving without stopping	4.1
	C3—Intuition-based reverse length change	Explanations that assume accelerating objects will elongate	Employs expressions based on the notion of length increase or stretching	2.2
	C4—Absolute length	Explanations grounded in the notion of absolute length	Assumes that the length of the object does not change	6.3
	C5—Galilean relative motion	Explanations grounded in the classical notion of relative motion	Employs expressions based on Galilean relative motion	2.1
	C6—Action-reaction principle	Explanations grounded in the action-reaction principle	States that the pole bounces off the barn or moves in the opposite direction	4.1
	C7—Momentum	Explanations that apply the concepts of momentum and collision	States that the barn and the pole move together	2.2
D—Responses lacking explanation		Blank or conceptually unjustified answers	Blank	6.2
Total				100.0

the barn at a velocity close to the speed of light, when the pole touches the far end of the barn it will push itself back out of the barn at approximately the same speed at which it arrived. This is what would happen if the barn were stationary. If the barn is also in motion, the barn will move together with the pole in the direction of the pole's motion.”

B. Students' understanding of the train-lightning paradox

The categories derived from the analysis of students' responses to the train paradox are presented in Table II.

The analysis reveals that 52% of student responses were grouped under Categories A1 and A2 of theme A. Of these, 27% fall within category A1, in which students were found to have selected the train as their reference frame and applied the concept of simultaneity. An illustrative example of this category is provided by S20's response: “The train will not explode because the speed of light is not dependent on the motion of the train. Both flashes detonate simultaneously and the detector perceives both at the same moment. We can board the train safely.” The remaining responses within this theme belong to category A2 and account for 25% of all responses. In these responses,

TABLE II. Students' responses to the train-lightning paradox.

Theme	Category	Definition of the category	Description of the category	%
A—Holistic or consistent application of relativistic principles	A1—Relativity of simultaneity within a single frame of observation	Explanations that acknowledge the simultaneity of events and are based on a single reference frame	Accepts that the flashes detonate simultaneously in the train's reference frame and that light reaches the detector at the same moment	27.0
	A2—Outcome consistent with the invariance of the speed of light	Explanations grounded in the constancy of the speed of light across all frames of observation and in relative velocity	Correctly applies the constancy of the speed of light and derives the conclusion that the train does not explode	25.0
B—Partial or inconsistent application of relativistic principles	B1—Impossibility of simultaneity	Explanations that acknowledge the absence of absolute time yet conclude that simultaneity is impossible	Concludes that, given the relativity of time, simultaneity is impossible under any physical conditions, and that the flashes cannot detonate at the same moment	8.0
	B2—Inconsistency with physical limits	Explanations that contradict the invariance of the speed of light despite accepting it	Accepts the constancy of the speed of light, yet arrives at the conclusion that an explosion occurs	2.0
C—Classical or intuitive reasoning-based explanations	C1—Variable speed of light	Explanations positing that the speed of light may vary depending on its source, direction, or motion	Assumes that one beam of light travels faster or slower than the other and resolves the paradox by applying the notion of relative motion	14.0
	C2—Wave model of light, dependent on the medium or conditions	Explanations that attribute the perception or propagation of light to environmental conditions	Produces a solution contingent upon the presence of reflective or illuminating objects in the medium	4.0
	C3—Momentum- or energy-based explanations	Explanations that employ the concepts of momentum or energy	Explains whether or not an explosion occurs in terms of the energy, momentum, or mechanical effect carried by the light or the flashes	6.0
D—Responses lacking explanation		Blank or conceptually unjustified answers	Explanations lacking a causal structure	6.0
			Unjustified explanations based on the position of the flash	6.0
			Blank	2.0
Total				100.0

students constructed consistent solutions by reasoning from the invariance of the speed of light. A representative example is S48's response: "In my view, the train will not explode. Because the detector can perceive light from both sides. Since the speed of light is constant, it reaches the detector simultaneously and no explosion occurs."

Ten percent of student responses were grouped under theme B. Category B1 within this theme is illustrated by S4's response concerning the impossibility of simultaneity: "The flashes cannot detonate at the same moment because, according to the relativity of time, such a situation is impossible. Therefore, even if only for an instant, one of the flashes will detonate later than the other and the train will explode." Category B2 comprises responses that, despite accepting the invariance of the speed of light, arrive at contradictory conclusions. An example is provided by S2's

response: "The speed of light is constant and very high. We would feel as though the flashes detonated simultaneously, but the time it takes them to reach the detectors differs by a fraction of a second. In this case, the train will explode."

The theme of classical or intuitive reasoning-based explanations accounted for 24% of student responses, encompassing accounts that treated the speed of light as variable, attributed changes in the propagation of light to environmental factors, or explained light in terms of mechanical effects such as energy or momentum. Representative examples from this theme are as follows:

From category C1, S7's response: "The train might explode because the detector is placed at equal distances. However, the speed of the light from the flashes also matters. We have no information as to whether the speed of the light emitted by the flashes is identical." And S25's

TABLE III. Students' responses to the twin paradox.

Theme	Category	Definition of the category	Description of the category	%
A—Holistic or consistent application of relativistic principles	A1—Outcome consistent with time dilation	Explanations that correctly state that time passes more slowly in a moving frame of reference	Applies the concept of time dilation in uniform motion and arrives at the conclusion that the twin aboard the rocket will be younger	16.7
	B1—Inverted application of time dilation	Explanations that accept time passes more rapidly in a moving frame of reference	Misapplies time dilation in uniform motion by stating that time will accelerate and arrives at the conclusion that the twin on Earth will be younger	6.3
B—Partial or inconsistent application of relativistic principles	B2—Correct conclusion with incomplete justification	Explanations that acknowledge a difference in time but fail to articulate the causal relationship	Employs the concept of relativity but does not account for the theory in terms of reference frames and accelerated motion	10.7
	C1—Location-dependent time dilation	Explanations that acknowledge a time-location relationship but are grounded in location rather than physical causation	Attributes the difference in time not to physical causes such as velocity, acceleration, or reference frame, but to the concept of “space,” employing generalizing expressions such as “time is slower/faster/different in space”	56.0
	C2—Explanations based on nonphysical environmental factors	Explanations that acknowledge a time-location relationship but attribute aging to factors beyond location alone	Employs generalizing expressions such as “time is slower/faster/different in space” and additionally accounts for the age difference through factors such as UV radiation and similar influences	2.0
C—Classical or intuitive reasoning-based explanations	C3—Perception of time dependent on location and distance traveled	Explanations grounded in a location-time relationship	Associates the flow of time with distance-related concepts such as the distance traveled and light-years	2.0
	D—Responses lacking explanation	Blank or conceptually unjustified answers	Contains statements without explanation	6.3
Total				100.0

response: “The train will explode. Because as the train moves to the right, one beam of light travels in the same direction as the train while the other travels to the left. One beam slows down while the other speeds up, and the train explodes.”

From category C2, S41's response: “If there is a surface along the track or at the sides of the track that reflects light, the light from the flash at the front of the train could be reflected and reach the detector. In this case, the train would explode. If there is no reflective surface alongside the track, the light would not reach the detectors, and the train would continue its way safely.”

From category C3, S15's response: “The train will not explode. The reason for this is the change in the train's momentum.” And S18's response: “It will not explode. If the train moving at the speed of light concentrates the energy in the air into a single point, an explosion may

occur. More than two flashes would be required for it to be more sensitive to the speed of light. The closer the two events are to one another, the more the principle of inertia can be satisfied.”

Student responses accounting for 14% of the total consisted either of explanations lacking a causal structure such as S42's response “Both flashes should not be set off at the same time,” and S6's response “When the flashes do not ignite, the train will not explode” or of unjustified explanations relating to the position of the flashes such as S38's response: “The train will not explode. Since both flashes are on the train, the flashes will not detonate.” One student left the answer sheet blank.

C. Students' understanding of the twin paradox

Students' responses to the twin paradox are presented in Table III.

The analysis reveals that theme A comprises responses from category A1 alone. It was determined that 16.7% of students used time dilation in their responses. Illustrative examples of this category include S4's response: "The twin outside Earth is younger. Because clocks inside a faster-moving object run more slowly" and S1's response: "There is no absolute time. There is no certainty in time. Time is relative. It can vary according to the observer. The twin who boards the rocket and travels is younger. Because in moving objects, time passes more slowly."

An examination of students' responses within theme B reveals that 6.3% produced responses falling within category B1 by misapplying time dilation in the reverse direction. S20's response, "The twin who remains on Earth appears younger. Because time passes more quickly aboard a rocket travelling at velocities approaching the speed of light. Unfortunately, upon returning to Earth, that twin will be older than the other," may be cited as an example of this category. A further 10.7% of responses fall within category B2, which comprises responses that express the theory of relativity merely as "time is relative." Representative examples include S30's response: "The twin who boards the rocket and travels is younger. Because there is no definite time. Time differs in different places." and S2's response: "Time is a relative concept. The person on Earth has lived 2–5 ss longer. That is, the twin who travels by rocket and returns is younger."

Student responses falling within category C1 accounted for 56% of the total and explained the slowing of time in terms of location. Representative examples include S34's response "The one on Earth is older. The one in space is younger. Because time passes more slowly in space" and S38's response: "The twin who remains on Earth is younger. Because outside of Earth, the concept of time is different and progresses more quickly." Category C2 comprises responses that ground the location-time relationship in environmental factors as well. An example is provided by S18's response: "The twin on Earth will be younger. Because time passes slowly on Earth. For a person travelling away from Earth, time will pass quickly in a place with greater exposure to light, and therefore someone travelling there cannot appear young. This is due to UV rays and radioactive radiation." In category C3, the flow of time is associated with distance-related concepts such as the distance travelled and light-years. A representative example is S32's response: "Time is faster in space. Therefore, the twin who travels away from Earth is younger. If they travel one light-year from Earth, that is very fast for the twin travelling in space. But for the one on Earth, one light-year is a very long period."

A further 6.3% of student responses consist of unjustified answers, such as S37's response: "Both are the same age" and S24's response: "The one who goes to space is younger. I forgot the reason."

D. Students' understanding of the grandfather paradox

Students' responses to the grandfather paradox are presented in Table IV.

The analysis reveals that only 4.2% of student responses were grouped under theme A. An illustrative example of this category is provided by S33's response concerning the impossibility of exceeding the speed of light: "Travelling to the past using a time machine would require attaining a speed greater than or equal to the speed of light. Were this to occur, the present time would need to be stopped or slowed down. This is impossible."

Student responses grouped under theme B accounted for 12.6% of the total. Category B1 is illustrated by S1's response, in which an attempt is made to express both absolute time and the concept of relativity: "We explain it through the theory of absolute time. Absolute time is relative. There is no absolute certainty." Category B2 comprises responses arguing that an intervention in the past would create a new universe or timeline. Representative examples include S5's response "If we travel to the past and kill our grandfather, we will have created a different future. We may also alter our own future" and S47's response: "The time traveller will have passed into a new universe (world). After the grandfather dies, a new dimension is created, and the traveller will never have existed in the place they originally came from."

A further 45.9% of student responses explained the principle of causality using notions unrelated to the theory of relativity, such as annihilation, simultaneous existence in different time periods, observing the past as a spectator, manipulating time, and altering kinship ties. These responses were grouped under the theme of classical or intuitive reasoning-based explanations. Of these, 18.6% fall within category C1, comprising responses that state one will cease to exist upon intervening in time. Examples include S20's response "So I travelled with a time machine and killed my grandfather. As a result, I went back to that time and killed my grandfather. But if I return to my own time, I may find that I no longer exist meaning I cannot do it, but someone I know might" and S25's response: "If he kills his grandfather, he will instantly die as well. Because without his grandfather, his father would not have existed. Without his father, he himself would not have existed. By killing his grandfather, he indirectly causes his own death." Category C2 comprises responses in which students argue that the past and future will continue simultaneously alongside one another. An example is provided by S17's response: "That person goes back in time and kills their grandfather. But the future is continuing so there are now two time periods. While the future continues, actions are being taken in the past simultaneously. The grandfather dies in the past. But since time continues in the future, the grandfather continues to have lived in the future as well."

TABLE IV. Students' responses to the grandfather paradox.

Theme	Category	Definition of the category	Description of the category	%
A—Holistic or consistent application of relativistic principles	A1—Causality-based impossibility	Explanations that invoke the principle of causality and the limits of relativity to argue that intervention in the past is impossible	Argues that the grandfather paradox is physically impossible by reference to the speed of light limit, causal ordering, and physical laws	4.2
B—Partial or inconsistent application of relativistic principles	B1—Conflation of absolute time and relativity	Explanations that employ the concepts of absolute time and relativity together, but inconsistently	Employs self-contradictory expressions such as “absolute time is relative”	2.1
	B2—Recognition of causality resolved through an alternative	Explanations arguing that intervention in the past creates a new universe or timeline	Recognizes the principle of causality and generates alternative scenarios such as “a different future,” “a different dimension,” or “a new universe” to circumvent it	10.5
C—Classical or intuitive reasoning-based explanations	C1—Assumption of annihilation	Explanations that resolve the principle of causality through the annihilation of the individual	Argues that the person who intervenes in time will cease to exist	18.6
	C2—Simultaneity of two-time planes	Explanations arguing that the past and future exist as two independent, simultaneous time planes	States that the future continues uninterrupted and that actions taken in the past do not directly affect the present	10.5
	C3—Impossibility of intervention in the past	Explanations arguing that events cannot be altered, even if the past is visited	States that the past has already occurred and can only be observed, not changed	10.5
	C4—Mechanical forward-backward manipulation of time	Explanations that treat time in a mechanical manner	States that temporal ordering can be advanced or rewound like a dial	2.1
	C5—Reconfiguration of kinship	Explanations that attempt to resolve the paradox by altering family relationships	Reconfigures the biological connection through expressions such as “he is not my real grandfather” or “my grandmother married someone else”	4.2
D—Responses lacking explanation	Blank or conceptually unjustified answers		Contains statements without explanation	6.3
			Blank	31.0
Total				100.0

Responses arguing that one can travel to the past but cannot intervene and can only observe as a spectator were placed in category C3. An example is S10's response: “Someone who travels to the past using a time machine cannot actively do anything in that past time. We can only observe the past. Since we are unable to prevent events from occurring, we continue to exist.” Category C4 comprises responses, such as that of S26, that treat time as a mechanical phenomenon capable of being advanced or rewound like a dial: “I would advance time by one step and watch my grandfather being born. Then I would rewind it by one step and watch my grandfather dying. The paradoxical situation is that time can be advanced and

rewound too many times.” Responses involving alterations to kinship ties were grouped under category C5. Examples include S14's response: “If I travel back in time and my grandfather is killed, my grandmother may have married someone else” and S48's response: “If I travel back in time and my grandfather is killed, my grandmother may later have remarried. In fact, the one I killed is not my real grandfather.”

A further 6.3% of student responses consist of unjustified answers lacking a causal structure, such as S11's response: “This contradiction continues” and S28's response: “My brain has encountered an error. I will think about this in more detail if a time machine is invented and it

is my turn to use it." A total of 31% of students left the answer sheet blank. It was determined that 37.3% of student responses were grouped under this theme.

IV. DISCUSSION

This study examined how undergraduate students resolved paradoxes by drawing on the fundamental concepts and postulates of the special theory of relativity. Paradoxes are thought experiments in which two different methods of resolution appear to yield contradictory outcomes yet ultimately lead to a single conclusion [19]. Students were encouraged to employ two distinct solution pathways, adopt two different perspectives, and arrive at a single answer. The findings indicate that students' responses to the paradoxes reflected a range of conceptual approaches, spanning from the holistic application of the theory of relativity to explanations grounded in classical physics and responses offering no explanation whatsoever. Even in solutions where students applied the theory of relativity holistically, they were unable to utilize multiple frames of reference simultaneously; instead, they constructed their explanations within a single reference frame.

A closer examination of the findings reveals that 33.3% of students in the pole-barn paradox and 27% in the train paradox were able to apply core relativistic concepts such as Lorentz contraction, time dilation, and simultaneity, producing solutions consistent with the principle that the laws of physics are identical in all inertial frames of reference. In the twins paradox, however, only 16.7% of student responses addressed time dilation within the context of a constant-velocity reference frame. The theme of partial or inconsistent application of relativistic principles accounted for 35.4% of responses in the pole-barn paradox, 10% in the train paradox, 17% in the twins paradox, and 12.6% in the grandfather paradox. Students frequently applied the postulates of the theory of relativity partially or inconsistently and, in some instances, produced solutions based on classical physics. The theme of classical/intuitive reasoning-based explanations accounted for 25.1% of responses in the pole-barn paradox, 24% in the train paradox, 60% in the twins paradox, and 45.9% in the grandfather paradox.

It may be concluded that approximately half of the participating students experienced considerable difficulty in correctly applying the fundamental postulates of the special theory of relativity to the paradoxes. At first glance, this difficulty might appear to stem from students' unfamiliarity with individual concepts such as simultaneity, time dilation, and length contraction. However, when the findings are considered collectively, they indicate that students were unable to utilize the concept of a reference frame as a functional analytical tool, nor were they able to evaluate the foundational principles of the theory of relativity holistically across multiple frames of reference. Alstein *et al.* [7] examined the teaching of the special

theory of relativity at lower undergraduate levels, identifying learning difficulties related to the use of reference frames, the postulates of the theory, and relativistic effects. Consistent with these findings, students in the present study interpreted concepts such as simultaneity, time dilation, and length contraction exclusively through a single reference frame. This, in turn, rendered the application of the fundamental postulates, namely, the constancy of the speed of light and the invariance of the laws of physics across all inertial reference frames, considerably more challenging.

These findings are in accordance with the studies of de Hosson *et al.* [6] and Alstein *et al.* [7]. As found in the literature, students tend to perceive relative motion solely as events observed from a fixed reference frame on the ground [7]. Similarly, difficulties have been reported in conceptualizing a reference frame as a group of observers at rest relative to one another [6]. In the present study, students were likewise observed to associate the reference frame predominantly with a single physical object—the barn, the train, or the rocket. In the pole-barn paradox, students adopted the barn as the reference frame; in the train paradox, the train; and in the twins paradox, a rocket traveling at constant velocity. Conversely, students did not treat the moving pole or an external observer watching the train as alternative reference frames, nor did they account for the effects of accelerated motion on the twin aboard the rocket. Students were unable to conduct analyses from the perspective of moving systems. While they could identify a reference frame with a single physical system, they struggled to treat moving systems as alternative frames of reference. This may be interpreted as an indication that students were unable to consistently apply the multiple reference frames required by the theory of relativity and could not simultaneously coordinate the perspectives of different observers.

Students tend to treat the concept of a reference frame not as a higher-order conceptual tool (one that is essential for the accurate understanding and application of the special principle of relativity) but rather as an ornamental expression devoid of any explanatory function [28]. Consistent with this observation, the undergraduate students in the present study frequently treated the concept of a reference frame as a superficial expression rather than as an analytical instrument for elucidating the theory. It is evident that students have not developed a sufficiently deep understanding of the role that the reference frame plays within the theory of relativity. Students across different age groups experience considerable difficulties with the foundational ideas underpinning the concept of a reference frame [29]. Many students do not conceptualize a reference frame as a system of observers for whom any given event occurs at the same time. Rather, students tend to perceive a reference frame not as an abstract measurement system, but as a concrete structure tied to a specific

physical object [28]. Such difficulties impede students' understanding of the relativity of simultaneity and adversely affect their ability to apply Lorentz transformations correctly [10]. As students do not adequately take the reference frame into account when defining physical quantities and events, they demonstrate a tendency to treat concepts such as simultaneity, time, and length as absolute properties.

The simultaneity of two events is not absolute. Two events occurring at different locations simultaneously within a given reference frame are not simultaneous in any other reference frame. A reference frame may be defined as a set of observers who are at rest relative to one another. These observers determine identical spatial distances and temporal intervals between any set of events, where an event is defined as a phenomenon occurring at a specific location in space and at a specific point in time [6].

Students' responses indicate that they regarded simultaneous events as absolute. In this regard, many students interpreted the relativity of simultaneity as being determined by the light signals reaching the observer, treating this as a perceptual difference rather than a physical measurement problem. In the present study, students' use of intuitive expressions such as "in our eyes" or "normally" in their solutions to the pole-barn and train paradoxes, alongside responses asserting that simultaneity is physically impossible, indicates that students perceived simultaneity as a matter of perceptual difference rather than a physical phenomenon. For instance, in the train paradox, while some students were able to reach correct conclusions by applying the constancy of the speed of light, others argued that simultaneity varies depending on the time it takes for light to reach the observer. Similarly, students who applied Lorentz contraction in the pole-barn paradox or time dilation in the twins paradox remained confined to a single reference frame. In addition, some students resorted to explanations rooted in classical mechanics, including collision, fracture, rebound, explosion, and variation according to environmental conditions. In constructing these explanations, students conflated the order in which two distinct events occurred as found in Ref. [17].

Even when two observers share the same reference frame, students believe that events may be simultaneous for one observer yet nonsimultaneous for the other. This is frequently explained in the literature as students associating the order in which two events are perceived with the order in which they actually occur [6]. In this view, the order of perception is assumed to determine the order of occurrence. However, when the distance between the events and the observer is taken into account, it is the travel time of the signals reaching the observer rather than the order in which the events occurred that determines perception. This leads to an interpretation in which causality appears to operate from future to past. Consequently,

when no distinction is drawn between the order in which an event occurs and the order in which it is perceived, the relativity of simultaneity is not recognized by students as a problem at all. In solving problems, the fundamental concepts of special relativity, the reference frame, simultaneity, and the role of the speed of light are therefore readily overlooked.

Such conceptual deficiencies appear to become particularly pronounced in students' responses to the grandfather paradox. A considerable proportion of students attempted to resolve the paradox not by addressing the principle of causality within the framework of the theory of relativity, but by resorting to explanations involving annihilation, alternative timelines, or parallel universes [18,19,30]. This suggests that students are unable to treat the concepts of time, causality, and reference frame in an integrated manner and consequently tend toward intuitive and everyday explanations rather than engaging with the physical constraints prescribed by the theory of relativity. Rather than confronting the counterintuitive nature of special relativity, which stands in direct conflict with everyday experience, students demonstrate a tendency to preserve their existing cognitive schemata, falling back on their intuitions and gravitating toward explanations grounded in classical physics, similar to findings reported in the literature [6,7,10,13,28].

The transition from classical to relativistic kinematics necessitates a fundamental shift in the conceptual framework. In special relativity, the constancy of the speed of light across all inertial frames of reference constitutes a foundational principle that determines the interdependent structure of space and time. However, the present study found that rather than using the postulate of the constancy of the speed of light, students relied upon a Newtonian velocity composition approach in their responses, interpreting relative motion within a classical physics framework. Students were found to formulate explanations suggesting that the speed of light could increase or decrease depending on the motion of the observer. These findings are consistent with studies in the literature demonstrating that students tend to interpret the speed of light through classical velocity addition rules [12,31]. Students' use of expressions such as "the pole breaks," "the barn shatters upon impact," "the pole bounces back," or "the barn and the pole move together" indicates that they drew upon classical physics concepts, including Newton's laws of motion, the action-reaction principle, and conservation of momentum, in formulating their responses. Such explanations correspond closely to the classical physics-based categories identified in the present study, particularly those involving the conflation of speed with force, collision and momentum-based interpretations, and the treatment of relative motion in classical terms. This suggests that students experience considerable difficulty in applying the first postulate of the special theory of

relativity, namely, that the laws of physics are identical in all inertial frames of reference to novel situations.

Furthermore, when the findings are considered collectively, it may be argued that this difficulty does not stem solely from an inability to apply the relevant laws of physics, but more fundamentally from a failure to develop a functional understanding of the concept of a reference frame. Rather than defining physical events in relation to a specific reference frame, students tend to approach them from an absolute and intuitive standpoint, which in turn leads them toward explanations grounded in classical mechanics. Similarly, the literature reports that students rely on classical physics intuitions when solving problems in modern physics and experience particular difficulty in applying relativistic principles valid at high velocities [17,29,32]. In this regard, paradoxes appear to serve as an effective means of revealing the tension between students' classical and relativistic modes of reasoning, while offering valuable opportunities for examining conceptual understanding.

The commonsense, experience-based conceptions rooted in classical physics that students hold stand in direct conflict with the postulates of the special theory of relativity [33]. This requires a fundamental restructuring of individuals' mental representations of space and time [34]; nevertheless, a considerable proportion of students remain unable to disengage from a mode of thinking grounded in Newton's conception of absolute time and space. In the present study, students similarly resorted to classical assumptions, namely, that time flows uniformly for all observers and that events occur within an absolute temporal framework, in their attempts to resolve the paradoxes. Yet the special theory of relativity fundamentally challenges these assumptions by demonstrating that time and space vary depending on the observer. In this regard, the findings suggest that students tend to acquire a superficial rather than a conceptually deep understanding of the theory of relativity and are unable to grasp in an integrated manner the fundamental distinction between classical physics and relativity.

Studies in the literature likewise emphasize that students are unable to distinguish between the concepts of observation and event and that this failure constitutes a significant barrier to their scientific understanding [14,15]. This is particularly evident in the present study in the context of the train paradox, where students evaluated the simultaneity of events according to the moment at which light signals reached the observer. Similarly, in the grandfather paradox, students' attempts to account for interventions in the past through annihilation or alternative scenarios reveal a conflation of the physical conditions under which events occur with the observational consequences of those events. Taken together, these findings indicate that students are unable to distinguish between the moment at which an event occurs and the moment at which it is perceived and

that this inability constrains their understanding of relativistic concepts.

The theory of relativity holds that the temporal ordering of certain pairs of events may be perceived differently by different observers. From the perspective of the theory of relativity, the principle of causality requires that the temporal ordering of events in terms of cause and effect must remain identical for all observers. The most significant point at which the special principle of relativity converges with the principle of causality is the conclusion that the speed of light cannot be exceeded. Yet in their solutions to the paradoxes, students either attempted to modify the speed of light through numerical methods such as relative or accelerated motion or circumvented the constraint altogether by travelling back in time and constructing alternative life scenarios. The concepts invoked in resolving the paradoxes became increasingly abstract and progressively removed from the conceptual vocabulary of classical physics. Students' responses indicate difficulties in moving beyond classical physics intuitions, and increasing difficulty in interpreting concepts as their level of abstraction increases [32,35].

This situation is consistent with studies demonstrating that students experience difficulty in transferring their existing classical physics-based cognitive structures to new and counterintuitive concepts [29,32]. Students frequently attempt to explain abstract concepts such as time, space, and simultaneity through intuitive frameworks derived from everyday experience and tend to employ these concepts in a decontextualized manner. This may also be related to students' inability to situate scientific concepts within appropriate ontological categories. Chi [36] notes that students often attempt to make sense of process-based and abstract concepts through object-based cognitive structures and that this tendency gives rise to conceptual errors. In this regard, it may be argued that concepts such as time and space within the special theory of relativity are approached by students in a superficial and fragmented manner [35,37], which in turn prevents them from achieving an integrated understanding of the foundational principles of the theory.

Students' various knowledge gaps concerning special relativity emerge across all levels of education, including secondary school, undergraduate study, and preservice teacher training [7]. Moreover, even after completing a course or receiving instruction in special relativity, students continue to rely on classical physics when solving relativistic problems [6]. Students demonstrate a preference for using absolute terms throughout their learning processes [17]. In the present study, students' intuitive or physically inconsistent responses in their solutions to the paradoxes such as "the train appears to explode," "energy accumulates somewhere and causes an explosion," "we transition to a new universe," "these events occur in two

parallel universes and do not affect one another,” or “a new future is created” indicate that students drew upon perception and optical illusions rather than the special theory of relativity. Similarly, students’ attempts in their responses to determine the numerical value of the speed of light in units of c , their solutions referring to time passing more slowly in space relative to Earth, and their assertions that length becomes zero, further demonstrate that they relied on classical physics laws in their calculations and conducted measurements accordingly. Hughes and Kersting [38] similarly found that students accounted for changes in time intervals or the dimensions of objects not through the theory of relativity, but through alternative explanations such as perception, optical illusions, or measurement error. The findings of the present study indicate that, in addition to their tendency to evaluate events within a single reference frame, students experience difficulty in applying concepts to novel situations owing to a lack of deep conceptual understanding.

V. CONCLUSIONS

This study aimed to describe undergraduate students’ conceptual understanding of basic special relativity concepts through four paradoxes, which serve as inverted, contradictory problems that require deep, conscious analysis. From the phenomenographic analysis of the students’ responses to these paradoxical problems, four main findings emerged. First, in the pole-barn paradox, a significant proportion of students were able to apply core relativistic concepts such as Lorentz contraction, simultaneity, and reference frames in a coherent manner, although a considerable number of responses also reflected partial or inconsistent application of these principles. Second, in the train paradox, students demonstrated a similar pattern, with some successful application of relativistic reasoning, while others relied on classical or intuitive explanations. Third, in the twins paradox, the majority of students tended to explain the situation using classical physics-based or intuitive reasoning, with relatively fewer responses correctly applying time dilation within a consistent relativistic framework. Finally, in the grandfather paradox, students predominantly produced explanations grounded in everyday intuition and classical causal reasoning, often without appropriate use of relativistic principles.

Taken together, these findings reveal that while students are able to establish superficial connections between concepts with relative ease, they are unable to develop a deep understanding of the physical meanings of those concepts and the relationships between them. Many students are unable to conceive of relativity as a genuine physical phenomenon [39]. Even in cases where students arrived at intuitively correct conclusions, they were unable to ground those conclusions in sound scientific reasoning and experienced considerable difficulty in justifying them. It is evident that the conceptual shift between

classical physics and the special theory of relativity has not taken place at a cognitive level in these students. This may be explained by students’ inability to distinguish between what actually occurs and what the observer perceives [14,15].

In resolving paradoxes of this kind, students are required to develop a perspective that acknowledges events may be perceived differently across different frames of Ref. [6]. However, students generally believe that relativistic effects manifest only at velocities approaching the speed of light [34]. This is particularly evident in the present study in students’ explanations, where relativistic effects are consistently conditioned upon the requirement of being “close to the speed of light.” For instance, some students stated that the pole would contract only at velocities approaching the speed of light (S12), indicating that they regarded relativistic effects not as a general principle but as a special case contingent upon a specific velocity threshold. Similarly, expressions such as “if the speed of the pole exceeded the speed of light...” (S14) reveal that students conceptualized the speed of light not as an upper limit, but as a critical threshold that determines the onset of relativistic effects. The fact that some students resorted to classical physics-based explanations, such as collision, fracture, or momentum, rather than drawing directly upon relativistic concepts in their solution processes, suggests that they considered relativistic effects to be valid only under conditions of extreme velocity and believed classical physics to be sufficient in all other circumstances. This indicates that students regard relativity not as a general theory applicable to all situations, but as an explanatory framework that comes into effect only at high velocities. Some researchers attribute this to the fact that the special theory of relativity is typically taught in advanced stages of education and believe that introducing its teaching at an earlier age would have a positive impact on this situation [7,17,19]. Incorporating the special theory of relativity and other topics from modern and contemporary physics into school education at an earlier stage would facilitate the conceptual transition between classical physics and the special theory of relativity [2,4,34,40].

Paradoxes are among the most effective thought experiments available for use in the teaching of the special theory of relativity. However, as the findings of this study demonstrate, students must possess a sufficient level of conceptual readiness in order to resolve dilemmatic experiments such as paradoxes. When the most fundamental concepts of the special theory of relativity, namely, the frame of reference, the observer, and the event, are inadequately understood, paradoxes appear merely as contradictions and fail to contribute to the learning process. In this regard, it may be argued that paradoxes can serve in the teaching of the special theory of relativity not merely as engaging illustrative examples but also as assessment

instruments that afford insight into the relationships between students' existing intuitive and classical physics-based modes of reasoning and their scientific conceptual understanding. In the present study, paradoxes were used following instructions to evaluate students' ability to apply their acquired knowledge and to determine the extent to which students were able to reason by taking multiple frames of reference into account, distinguish between events and observations, and apply the foundational postulates of the theory of relativity in an integrated manner. In this respect, paradoxes afford the opportunity to identify the distinction between students' surface-level and deep learning and to observe the processes of conceptual change. The use of paradoxes as an assessment tool following instruction in the special theory of relativity may be regarded as an effective approach for determining the extent to which students are able to make sense of counterintuitive concepts and the degree to which they have developed scientific reasoning skills.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they are owned by a third party, and the terms of use prevent public distribution. The data are available from the authors upon reasonable request.

APPENDIX: DATA COLLECTION TOOL

1. Inventory on paradoxes related to the special theory of relativity

Dear Students,

This inventory has been prepared as a data collection instrument for the academic study titled "Undergraduate Students' Application of Special Relativity Theory to Paradoxes." The purpose of this study is to determine the application level of students' knowledge. Below are paradoxes containing dilemmatic physics problems that you frequently encounter in both physics' textbooks and popular science magazines. These paradoxes are a type of thought experiment scenarios that we cannot experience in our daily lives but can mentally design and solve using our physics knowledge. You are expected to provide a solution for each of these thought experiments in the space provided beneath them. Participation in this study is voluntary. There is no need to write any personal information on the answer sheet. Your responses will not be shared with any individual or platform, nor will they be assessed as a measure of your academic success.

Thank you for your sincere answers, for your time, and for contributing to our study.

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Paradox 1: The Pole-in-the-Barn Paradox

Imagine a pole with a length of one metre and a barn with an internal space of one metre. These lengths represent the normal, static lengths of the objects. If both objects are at rest, it is possible to place the pole inside the barn and close the lid.

Now, let us imagine that the pole is not gently pushed into the barn, but is instead hurled at great speed. To illustrate the problem more clearly, let us exaggerate and assume that the pole's velocity is close to the speed of light.

Question: Can we place the pole inside the barn and close the door? Explain your reasoning.

Paradox 2: The Train-Lightning Paradox

Consider a train travelling in pitch darkness at night. Two flashes are placed at the very ends of the front and rear carriages of the train. A detector is located in the middle of the train, equidistant from both flashes. Both faces of the detector are sensitive to light and detect whether or not light falls upon them.

Assume that the detector is connected via a circuit to a set of explosives. If light falls on only one face of the detector, the mechanism is triggered, and the explosives detonate, causing the train to be destroyed. However, if light falls on both faces simultaneously, nothing happens, and the train continues safely on its journey.

Question: Assuming you detonate both flashes simultaneously in the pitch darkness, will the train be destroyed or not? Explain your reasoning.

Paradox 3: The Twin Paradox

Assume that one of two twin siblings boards a rocket and travels away from Earth at a constant velocity, while the other sibling remains on Earth. Imagine that after a certain period, the travelling sibling returns to Earth and meets their brother/sister.

Question: Which of the siblings will be younger at the time of the reunion? Why? Explain your reasoning.

Paradox 4: The Grandfather Paradox

Assume you have a machine that allows you to travel back in time to the past. You use this machine to go back to the time before your grandfather was married. You then cause your grandfather's death.

If your grandfather did not marry and have children, then you should never have been born. In that case, no one could have used the time machine to kill your grandfather.

Question: How can you explain this contradiction?

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