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STUDENT DIFFICULTIES IN SOLVING PROBLEMS CONCERNING SPECIAL RELATIVITY AND POSSIBLE REASONS FOR THESE DIFFICULTIES

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Abstract. *There are two main purposes of this study. The first is to determine the basic difficulties of students in solving problems about the theory of special relativity, and the second is to identify the possible causes leading to these difficulties. To achieve these goals, 3 open-ended questions were administered to the participants. These questions were answered by 78 students who had been enrolled in a modern physics course. Out of 78 students, 24 students were selected for interviewing. Commonly used textbooks were also analyzed in order to determine whether there are differences in content. The results of the analysis showed that the students had difficulties in selecting the proper frames of reference. In addition, they could not use the concepts included in the fundamental equations accurately in accordance with their meanings. The main reasons behind these difficulties seem to be the improper generalizations of students. Moreover, the different representations of the fundamental equations in the various textbooks were also seen as the reason for the difficulties students encountered.*

Key words: *problem solving, student difficulties, special relativity.*

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Introduction

The subject of the "Theory of Special Relativity" in modern physics often drags students into complexity by introducing them to unexpected and surprising results. For example, the students are confronted with the concept of change in length, time and motion for the first time in this course.

Understanding these new concepts is quite difficult for students, although most of them find these interesting (Scherr, Shaffer & Vokos, 2001; Scherr, Shaffer & Vokos, 2002; Scherr, 2007; McGrath, Savage, Williamson, Wegener & McIntyre, 2008; Selçuk Sezgin, 2011). In general, the main applications of this subject are beyond their daily experiences. Additionally, students do not have the opportunity to directly experience any similar form of these applications. Therefore, this subject and its applications are found to be quite abstract by students (Scherr et al., 2001; Scherr et al, 2002; Belloni, Wolfgang, Dancy & Melisa, 2004; Guisasola, Solbes, Barragues, Morentin & Moreno, 2009; McGrath, Wegener, McIntyre, Savage & Williamson, 2010; Weiskopf, 2010; Selçuk Sezgin, 2011). However, a review of the relevant literature has shown that the number of studies about this topic is less than that of the studies on more concrete topics like mechanics, electricity and magnetism. In other words, there are only a few studies addressing students' difficulties about this abstract topic. Highlighted difficulties and misconceptions related to this subject in the literature can be summarized as follows.

Student difficulties in selecting a proper frame of reference is problem experienced in the study of the special theory of relativity. Students have difficulties in understanding and creating these frames of reference, and they also cannot use them for different observers (Scherr et al., 2001; Scherr et al, 2002; Belloni et al., 2004; Guisasola et al., 2009). They have wrong ideas about the time of occurrence of the events that transpired in the different reference frames. For example; "… *Many seem to believe that the time of a distant event is the time at which a signal from the event is received by an observer. Thus, they treat the time ordering of two events as dependent on the location of an observer…* " (Scherr et al, 2002).

Students think that time dilation is unilateral and they have misconceptions about proper time (Sezgin Selçuk, 2011). Some students believe that length contraction can occur in all dimensions of an object, independent from the direction of movement (Scherr et al, 2002; Belloni et al., 2004; Sezgin Selçuk, 2011).

In addition to the points mentioned above, experiences have shown that students have some problems about this topic at the end of the teaching process. Generally, students can explain the principles of special relativity. They can express the results of these principles, but they have difficulties in the application of these principles in solving problems. In a study conducted by Özcan (2011), students' problem solving approaches in problems of special relativity were examined. The researcher concluded that students have serious difficulties in solving relativity problems since they do not use a scientific and strategic approach. It is thought that students' ideas need to be investigated in detail in terms of the basic difficulties they experience with the subject of special relativity and the reasons behind these difficulties.

This study, therefore, aims to find out what difficulties students experience and the reasons behind these difficulties that lead them to misconceptions. For these purposes, the present study focuses on the difficulties in understanding of frames of reference and creating frames of reference, determining and identifying proper and affected quantities, using these quantities in mathematical equations while solving problems involving the dilation of time and the contraction of length.

Methodology of Research

General Background of Research

In this study, student difficulties related to the theory of special relativity were investigated in detail. Both quantitative and qualitative research methods were used for carrying out this research. The methodologies of the studies that include more than one research techniques are named as mixed research methods, as mentioned in a study by Leech and Onwuegbuzie (2007).

Sample Selection

In one study, if a sample is selected according to the research aims and the participants are selected from individuals having certain qualifications, this sampling method is named as a criterion sampling that is under the umbrella of the purposeful sampling method (Patton, 2002; pp. 230, 238). In this study, the participants were selected from among students enrolled in a course on Modern Physics. It can therefore be said that the sampling method of the study is the criterion sampling. The sample of the study consists of 78 students studying in the physics education department (36 students) and in the science education department (42 students) of a public education faculty in Turkey. The students in the physics education department are trained to teach only physics topics to high school students. The students in the science education department are trained to teach general science (physics, chemistry and biology) topics to junior high school students. Therefore, the students in the physics education department receive a more detailed education about the topics in physics compared to the students in the science education department. Also, all participants had a previous background of learning the topic of special relativity prior to this study.

Research Instrument and Procedures

The main research instrument of the study consists of 3 open-ended questions related to the theory of special relativity. The first and second questions are about the consequences of the principles of special relativity and formulations of these consequences. The other question contained three sub-problems aiming to assess whether the students could apply their subject knowledge to solve a problem. The questions were prepared by the researcher to reveal students' ideas that were wrong, but compatible or correct, but misapplied, as indicated in the study of Scherr (2006).

Students were asked to answer the open-ended questions in 50 minutes and the time given was found to be enough for all. When the administration time was over, the papers were collected.

The group for qualitative analysis was selected according to the students' scores based on their responses. They were classified as high, medium and low achievers in their classes (physics education and science education). Twelve students in the physics education group (4 high, 4 medium and 4 low) and 12 students in the science education group (4 high, 4 medium and 4 low) were selected; thus, the qualitative research group consisted of 24 students.

Semi-structured interviews were carried out with the qualitative research group (N=24), to determine the students' ideas and how they used their subject knowledge when answering the questions. Interviews were conducted based on the question and solution sheet for each student. These conversations provided detailed information about what they wrote and drew on the solution sheets. Thus, the aim was to determine their ideas based on understanding and comprehension in addition to ideas based on memorization. Each interview took approximately 25 minutes and was recorded to avoid loss of data.

As indicated in the literature, although the content of the topics are correct in textbooks, differentiations at the presentation of content may cause difficulties for the students (Justi & Gilbert, 2002; Rudowicz & Sung, 2003; Gericke & Hagberg, 2010). As such, the textbooks commonly used as source books for modern physics courses in Turkey were examined in order to determine whether there were similarities/differences in content and presentation for related topics. Some of them were books by Turkish authors and some of them were books translated into Turkish (Keller, Gettys & Skove, 1995; Serway, 1996; Taylor & Zafaritos, 1996; Beiser, 1997; Bueche & Jerde, 2000; Fishbane, Gasiorowicz & Thornton 2003; Özdoğan, Kara, Gümüş & Orbay, 2005; Ünlü, Kandil İngeç, Budak & Erduran Avcı, 2006; Young & Freedman, 2010).

Data Analysis

Tekindal (1998) reported that analytic scoring method is the most reliable method among others to score written exams. The answer key for each question was scored beforehand using the analytic scoring method in an attempt to evaluate students' responses more objectively. Two people evaluated the papers to ensure the reliability of the evaluation method and the papers were evaluated with respect to the scoring method determined previously (Bekiroğlu, 2004). Students' responses were classified and scored; answers that were completely wrong or included misconceptions were scored as 0 points. The answers that were incomplete and included some correct knowledge and proper use of facts were scored as 1 point and, the answers were completely correct were scored as 2 points. The data were examined considering the scoring criteria by the researcher and an expert in physics education. The scores obtained were compared statistically and the Pearson correlation value for the scores was found to be 0.872 ($p=0.00<0.01$). As a result of this assessment, responding frequencies of the questions and scores of the students were determined.

The data obtained from semi-structured interviews were evaluated by using the qualitative descriptive analysis method. This method is based on determining the themes appropriate to a theoretical framework related to the research subject and then summarizing and interpreting the data (Yıldırım & Şimşek, 2005). Voice recordings of the participants were transcribed by the researcher. Lines of student responses were coded as S1, S2, and so on for each student. When analyzing the student responses, only inadequate and wrong answers were considered for the first and the second question. The ideas which were categorized according to three themes that were determined beforehand were evaluated in the analysis of the third question. The themes are as follows: students' approaches to the solution, the comments related to proper and affected quantities, and determining reference systems. The procedure described was repeated by the researcher after one month and the consistency was computed to be 93%.

The textbooks commonly used for modern physics courses were examined by researcher for fundamental content analysis. When examining the books, the following criteria were noted for the purposes of this study:

a) Displaying the frame of reference.
b) Displaying the equations used in the applications of time dilation and length contraction and the ways variables were expressed in these equations.
c) The structure of the example problems.

For the purpose of this study, fundamental similarities/differences in content and presentation of the books were determined.

Results of Research

In this section, the students' responses to each question and their ideas about them were analyzed separately. To report the results of the interviews carried out with the students, the researcher's statements were coded as R, the students' statements were coded as S1, S2, and so on.

Question 1(Q1): Thinking about the consequences of the principles of special relativity, please explain how these affect your conception about space (length, dimension) and time.

Frequencies:

65 (83.33%) students satisfactorily answered the first question. 5 (6.41%) students correctly responded only about effects on time and 4 (5.13%) students correctly responded only about effects on length. 4 (5.13%) students didn't make a comment.

Student Views:

From the inadequate or wrong responses of the students who were interviewed, selected common views about the first question are as follows;

R: *Do you think that your answer is completely correct?*
S14: *No, I guess it is not. Because my answer is incomplete. I remember that the length became shorter. I was not sure about the time.*
S19: *I think the length increases and the time decreases.*
R: *Is there a reason for not answering this question?*
S4: *Frankly, I don't remember anything about this topic. Special relativity was a very difficult subject for me.*

Question 2(Q2): If your concepts of space (length, dimension) and time have changed as mentioned in the first question, can you express your newly developed concepts mathematically?

Frequencies:

Of the students, 66 (84.62%) wrote both equations correctly. Five (6.41%) students wrote the factor $\gamma=\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ correctly but used it incorrectly (e.g., $L = L_o.\gamma$). Three (3.85%) students wrote the γ factor incorrectly as $\gamma=\sqrt{1-\frac{v^2}{c^2}}$. Four (5.13%) students didn't respond.

Student Views:

R: *Do you think that the equation you wrote down is right?*
S19: *According to me, it is right. Is it wrong?*
R: *It is wrong.*
S19: *In that case, my answers about time and length are also wrong.*
R: *How did you get this idea?*
S19: *I know that* $\gamma < 1$*. In this case, I must have put it into the equation wrongly.*
R: *What do you think the problem was when you were trying to write the equations?*
S1: *I could not remember how to use the equation* $\gamma=\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ *for calculating L - L' and t – t'.*
S4: *I always confuse the two expressions* $\gamma=\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ *and* $\sqrt{1-\frac{v^2}{c^2}}$ *, which one we are supposed to use and when…*

Question 3(Q3a/Q3b/Q3c)

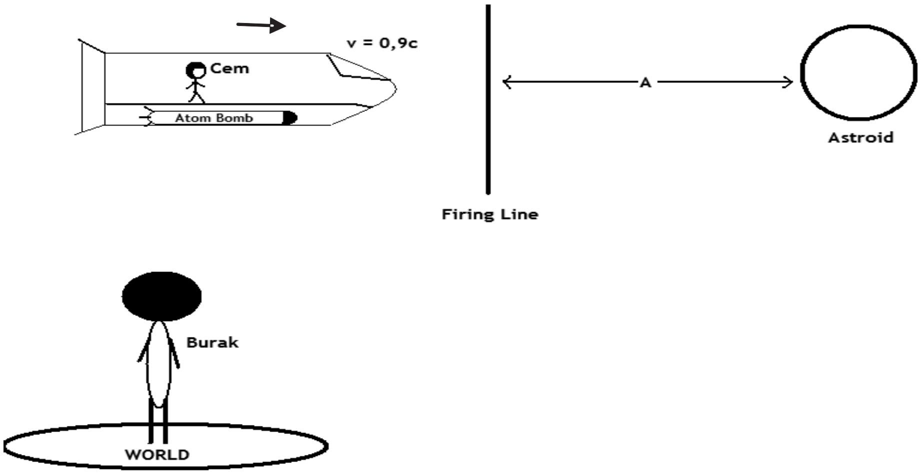

Figure 1. The figure in question 3.

Control tower officer Burak and astronaut Cem were given a mission: Blasting an asteroid approaching the world with a very low speed using an atom bomb. Two identical clocks showing the same time were given to Burak and Cem before the spaceship started the takeoff. Cem's spaceship approaches the asteroid with a constant speed of 0,9c after its departure as shown in Figure 1. Answer the following questions according to the information given. (All measurements below were made when the spaceship was moving at constant speed.)

Q3a) Cem measures the length of the bomb in the spaceship as 4 m. If control tower officer Burak measured the length of the bomb, how many meters would it be?

Q3b) Both of the observers measure the distance between the asteroid and firing line. Burak reports the length A as 2000 km. According to you, is the length reported by Burak true for Cem? If it is not, what would Cem measure?

Q3c) Both of the observers measure the time it takes from when Cem presses the launch button until the bomb leaves the spaceship, by using their own clocks. Cem reports the time as 5s. According to you, is it true for Burak? If it is not, what would Burak measure?

The answer to Q3a:

Here Cem is the stagnant observer relative to the bomb. Burak is the moving one relative to the bomb and, accordingly, relative to Cem. Let S be the frame of reference in which Cem and the bomb are relatively stationary, and let S' be the frame of reference in which Burak, who is in motion relative to S, is relatively stationary. The real length of the bomb measured by Cem is L_0; however, Burak measures it as L. Using the equation $L=L_0/\gamma$, it can be understood that Burak measures the length of the bomb as shorter.

Frequencies:

36 (46.15%) students gave the correct answer for this question. Thirty (38.46%) students wrote down the equation correctly but could not use it properly and 5 (6.41%) students wrote the equation incorrectly. Seven (8.97%) students did not respond.

Student Views:

- Students' approaches to the solution

R: *What do you think about the solution to the question?*

S3: *The one in the ship measures shorter. Because the length or distance measured by moving one was always shorter in the questions we previously solved.*

S5: *The one in the spaceship measures shorter. The lower one measures as L, the above one measures as L'.*

S9: *The observer in space sees it shorter. Length contraction occurs.*

S23: *The shorter one was in space. The one in the normal situation is the normal length. Then how can we find it now? …but which one is which? I am confused.*

- Students' comments on the concepts of proper length and contracted length

R: *How do you define the quantities used in the equation you wrote?*

S2: L_0 *is for the observer on the world.* L' *is for the moving observer.*

S18: L_0 *is the first length on the world. The other length is the length measured when it goes somewhere. I mean, it is contraction.*

S7: *L is the length of the object in the stagnant frame of reference.* L' *is the length of the object in the moving frame of reference.*

R: *Well, what do you mean by stagnation?*

S7: *I mean the observer is not moving.*

R: *Who do you define as the observer who is not moving?*

S7: *Burak.*

S12: *Stagnant time is* T_0 *and stagnant length is* L_0. *If it is moving, they become T and L.* T_0 *and* L_0 *are proper quantities and T and L are affected quantities.*

R: *Who do you define as the observer who is not moving?*

S12: *The one on the world, Burak is stagnant. I explained it according to this.*

S14: *The observer in the spaceship measures as* T' *and* L'. *The observer on the world measures as T and L. Stagnant observers measure L and T values but moving observers measure* T' *and* L'. *The measurements of the observers in the moving systems are* T' *and* L'. *The measurements of the stagnant observers are T and L.*

- The reference systems

Many of the students describe the reference system which includes Burak as S and the reference system of Cem as S'. The following are sample sentences:

R: *How do you determine the reference systems?*

S7: *The stagnant reference system is S and the moving one is* S'.

S14: *The spaceship is moving so it is* S' *and the stagnant one in the world is S*

The answer to Q3b:

The asteroid is approaching the world at a very low speed. In this situation, the stationary one relative to the asteroid is Burak. Cem is approaching the asteroid with a speed of 0.9c. The length A measured by Burak is L_0 but the length measured by Cem is L. So Cem measures the length A shorter. In this situation, the reference system including Burak is S and the reference system including the spaceship and Cem is S'.

Frequencies:

Fifty-nine (75.64%) students answered this question satisfactorily. 10 (12.82%) students wrote down the equation correctly but could not use it properly and 5 (6.41%) students wrote the equation incorrectly. Four (5.13%) students did not respond.

Student Views:

- Many of the students interviewed thought that the moving observer measures shorter and the observer on the earth measures longer. Some of the students indicated that the length measured by the stagnant observer was L_0 and the others indicated that it was L. They also stated that the length measured by the observer in the spaceship was L'. The following are sample sentences:

S5: *The one on earth again measures longer when compared to the measurement of the one in space.*

S20: *Burak measures longer because he is stationary.*

S2: *It can be again said that* L_0 *is for the observer on earth and* L' *is for the moving observer.*

S21: *The lengths measured are different. The one on the earth measures* L_0 *and the one in the spaceship measures L.*

- There are also notable explanations in the interviews:

R: *What kind of difficulties did you have when answering this question?*

S6: *I am not sure about the distances from the asteroid. It seems like the distances for both of them are the same.*

R: *Please explain why you think that?*

S6: *Both of them measure a quantity outside of their own systems. Burak is in the world reference system and Cem is in the spaceship reference system.*

R: *You said that both of them measured the same. Please explain your answer?*

S11: *Both of them measure the same because the asteroid is not included in the reference system of the world or the spaceship.*

- Some students answered the question without drawing the reference systems. Some of their responses when questioned about the reasons are summarized below:

R: *Why did you answer the question without drawing the reference systems?*

S6: *The asteroid does not belong to any reference system. Can it be included in one?*

S9: *We have the world, asteroids and spaceship in this question. All of them are at different positions; for this reason it didn't make any sense and I didn't draw anything. Length contradiction occurs for only a moving observer, so I solved the question accordingly without drawing any reference system.*

S15: *There are three different positions, but we know how to draw only two reference systems. For this reason, I couldn't draw a reference system for the third one.*

The answer to Q3c:

Cem observes the beginning and the end of an occurring event in his own reference system. Therefore the time he measures is the proper time t_0. Burak however, is moving according to the system in which the event occurs and the time measured should be equal to $t = t_{0.}\,\gamma$, where it>t_0. Because Cem is stationary according to the system in which the event occurs the reference system for the spaceship is S and that for the world is the system S′

Frequencies:

Forty-one (52.56%) students answered the question correctly. Twenty-four (30.77%) students wrote down the equation correctly but could not use it properly. Six (7.69%) students could not write the equation correctly and 7 (8.97%) students did not respond.

Student Views:

- Students' approaches to the solution

R: *How did you decide how you would solve the question?*

S7: *I understood the concept of time dilation in moving reference systems, but I couldn't remember whether the time dilation occurs for the spaceship or in the world. Time is wider and slower in moving systems and therefore more time has to pass. Therefore, less time passes according to the observer in the world.*

S10: *A person moving with the speed of light the space sees everything more slowly. When a clock tick-tocks normally, a person moving with a speed close to the speed of light hears the tick-tocks more slowly. For example, when s/he is stationary, s/he hears a tick-tock every 1 second but when s/he is moving, s/he hears a tick-tock every 3 seconds. Time passes fast in the world, but time passes slowly in the spaceship moving at a speed close to the speed of light. For example, in the twin paradox, the person on the world becomes older than the person in space.*

- Students' ideas on the concepts of proper time and time dilation

R: *How do you define the quantities used in the equation you wrote?*

S3: *5 seconds in this question is t because the astronaut is moving. T is the real value.*

S5: *5 seconds in this question is t because the observer is moving. According to the stationary observer staying in the world, it is t_0.*

S6: *The measurement of the person on the earth is t. The measurement of the person in the spaceship is t′. t becomes t′ by expanding, so we calculated the dilated time value of t′.*

S14: *The observer in the spaceship measures only t′ and l′; the observer on earth measures everything as t and l. The stationary observers measure l and t values, moving observers measure t′ and l′. The measurements of* *the observers in moving systems are t′ and l′. The measurements of the stationary observers are l and t. The measurements of the events whether in their own systems or in any other system don't change anything for the terms of t, t′, l and l′.*

S16: *Let's think about a shuttle sent to space. The time there is t′, because the observer is moving. It is t for the observer on earth.*

- Reference systems

Students usually think that the reference system including the spaceship is S′ because it is moving; and, they think that the reference system including the stationary observer on the world is S.

It is seen that the examples in the textbooks are generally based on the observations of the events occurring in a moving system, made by the stationary observer. For example, a stationary observer on the world measures the change of the length of a spaceship moving with a speed close to the speed of light. Accordingly, the frame of reference of the stationary observer is represented by S and the frame of reference being observed is represented by S′ in the solutions. However, it is seen that the symbols (such as t, t′, t_0, Δt, Δt′ and L, L′, L_0, ΔL, ΔL′) in equations represent different quantities in different textbooks. For example, t′ represents dilated time in one book, but proper time in another. It is also seen that the forms of the equations in different textbooks also differ.

Discussion

The evaluations that are made in the light of the results are as follows:

The rates of the correct responses given to the Question1 (Q1) and Question2 (Q2) are greater than the Question3 (Q3). This result supports the author's aforementioned experience, expressed in the introduction part of this study. In general, participants can express the changes that occur in length and time at speeds close to the speed of light. However, they have difficulties in applying their knowledge to solve problems about this topic. It can therefore be said that students only memorize the consequences of the theory of special relativity. These findings support the literature in a similar but different way. Students solve problems about objects that they are familiar with in their daily lives, but having speeds close to the speed of light. Such physical phenomena as motions of macro world bodies with speeds close to the speed of light are not real in everyday life. Thus, students do not have a chance to experience exactly the same situations described in problems concerning special relativity. For this reason, their lack of experience makes it hard for them to believe the obtained results implied by the solutions of these problems and prevents them from cross-checking to see whether their solutions are correct. It is stated in the related literature that the lack of daily experience makes topics more abstract and incomprehensible (Scherr et al., 2001; Scherr et al., 2002; Belloni et al., 2004; Guisasola et al., 2009; McGrath et al., 2010; Weiskopf, 2010; Selçuk Sezgin, 2011). It is thought that the difficulties described above can be prevented, if example problems are chosen from topics related to the motion of micro-world bodies/particles and the propagation of light (electromagnetic waves) such as the Michelson-Morley experiment, retardation of muon decay, the ultimate speed of sub-atomic particles and change in the propagation speed of waves in a material medium. As stated in Ziggelaar (1975)'s study, these topics are directly related to the consequences of relativity theory.

The results of the interviews on Q2 revealed that students prefer memorizing formulas to be used in solutions to problems. Wrong answers often resulted from the assignment of incorrect values to quantities like L, L_0, L′ and t, $t_{0,}$ $t^{'}$ in the formulas.

Q3a and Q3c can be claimed to be unusual types of questions for students because the observer who is thought of as relatively motionless is actually in motion. Q3b is about a more usual situation because the observer makes measurements in a motionless system. Based on the views obtained from the examination of the textbooks, this question can be characterized as a common question. This may be a reason for the difference between the number of correct answers given to Q3b and Q3a. It is reasonable to think that questions similar to the common examples existing in the textbooks can be solved more easily by students, compared to complex ones.

The data obtained from responses to Q3a and Q3b show that students make wrong generalizations. They think that length contraction occurs only in moving systems and does not occur in motionless systems. As specified in Scherr's (2006) study, this generalization can be thought as an example of ideas of students that are correct but improperly applied. It is true that length contraction occurs for an object that moves at speeds close to the speed of light. But according to whom? The students who have this generalization mostly do not take relativity into account. This situation leads them to the most common mistake in applications. For example, this generalization applies to Q3b but not to Q3a. This may be another reason for the difference between the number of correct responses given to Q3b and that of Q3a.

The evaluation of the student responses given to Q3c indicates that the concept of time dilation is perceived as a change in quantity by some of the students. According to these students, it takes more time for an event to occur. It is indicated in the literature that, student difficulties related to length contraction are rarer than those related to time dilation (Scherr et al, 2002; Sezgin Selçuk, 2011). The possible cause of this difficulty can be identified by using the finding above. At this point, the finding of this study is consistent with the literature. As a result of length contraction, an observer measures the decrease in length of the object physically. The discourse and the meaning both refer to the same thing. However, the discourse of dilation is perceived as an increase by some of the students, although the meaning is the opposite.

Interview results indicate that, students mostly perceive proper length and proper time as the measurements of an observer in a motionless system and measurements made in a moving system are perceived as contracted length and dilated time. Once again, it can be said that students usually do not take into account the relative positions of the observers. Of course, in some cases, this generalization is applicable. According to Scherr's (2006) study, this situation can be thought as an example of the ideas of students that are incorrect but applied correctly.

The main difficulty in determining frames of reference again results from incorrect generalization. The system of a stationary observer is generally defined as S and the system of a moving observer is defined as S'. This situation causes an inconsistency in determining the variables of t, t_0, t' and L, L_o, L'. Assigning incorrect values to variables also causes problems in applications. Interview results of Q3b also show that students perceive a reference system as the position of an object and do not take the events occurring into account. For example, some of the students think that the world, spacecraft and asteroid are individual references. These students miss the fact that all relatively motionless objects and observers are taken to be in the same reference frame.

According to students' ideas and examination of the textbooks, two other factors cause incorrect student generalizations. The first one is the twin paradox. Some students try to rationalize their incorrect generalizations by referring to the twin paradox. Variables measured in space and in the spacecraft are generally thought to be dilated time or contracted length. In the textbooks, special relativity is generally described by utilizing the same example involving a stationary observer on the world and a moving observer in a vehicle. In this situation, without being aware of it, we may be leading students to incorrect generalization. As stated in the Scherr et al (2002)'s study, paradoxes can be used to increase students' interest in the subject. As the authors note, the solution of paradoxes should be performed by students. Otherwise, only a very attractive endpoint in the teachers' solution will be memorable. These results may lead students to wrong generalizations as in the example of the twin paradox.

The other important points are thought to be the differences in the manners of presentation and expression of the subject across different textbooks. Although the expressions and representations in each book themselves are consistent and in line with scientific facts, the use of different notations in different textbooks may cause confusion if a student who has just started to learn this topic and who uses more than one textbook.

Conclusions

The results of this study showed that student difficulties in solving problems related with this topic result from the lack of applications. Problems usually include the motions of macro- world bodies at a speed close to the speed of light. Students who have difficulties in understanding these situations are led to wrong generalizations and memorize some of the key points of the topic. Mathematical equations deal with the quantitative relations of the real world. Therefore, in order to understand the meaning of the equations of this topic, students need to know the features of the real world where the problem situations arise. Therefore, problem-solving should be started with related micro-world phenomena. Also, solving different examples involving different cases, especially related to micro-world phenomena may help students to overcome these difficulties.

Experiments cannot be conducted easily in this topic, in a classroom environment. The use of related software will therefore help students to visualize the different cases.

Textbooks, that have a similar manner of presentation and expression of the subject, can be selected for the beginning of the course to prevent confusing the students. Also, students should be warned about the differences between the textbooks and should be reminded to learn the creation of equation rather than memorizing as seen in the book.

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