IJPCE
International Journal of Physics and Chemistry Education, *11*(2), 45-53

www.ijpce.org
ISSN: 2589-8876

Prospective Physics Teachers' Understanding of the Speed of Light within the Scope of Special Relativity

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Abstract

This study employs the qualitative method to investigate the concept structures of prospective physics teachers regarding the speed of light. For data collection, 46 prospective physics teachers were asked to draw concept maps related to special relativity. A total of 77 propositions were found in the maps. Content analysis was used for data analysis. 4 themes and 14 sub-themes were found as a result of the analysis. "The effect of the speed of light" theme had the highest number of propositions written by the prospective teachers. Some statements claiming the existence of speeds higher than the speed of light were found in "the property of the speed of light" theme. The findings can be interpreted as that students had difficulties with understanding the second postulate of special relativity.

Keywords

Prospective physics teachers; special relativity; speed of light

◆Received 05 September 2018 ◆Revised 19 November 2018 ◆Accepted 23 November 2018

Introduction

Although movement is a part of everyday life, almost all our experiences involve movements at much lower speeds compared to the speed of light. Until the 20th century, Newtonian mechanics has successfully solved all the problems related to movement. In 1905, the theory of special relativity published by Einstein, 26 years of age at the time, shattered all concepts taught in classical physics and suggested a new approach to understand the world.

The theory of special relativity consists of two postulates (axioms) and it is one of the greatest intellectual successes of all time. Using this theory, it is possible to accurately predict results of experimental observations in a large area up to the speed of light (Serway & Beichner 2005). According to the first postulate of special relativity, the laws of physics must be the same for all inertial reference systems. The second postulate, on the other hand, suggests that the speed of light is fixed in all inertial reference systems, independent of the observer and the source of light.

As a result of the postulates of special relativity, it was suggested that the concepts of length and time were relative, which had previously been accepted to be absolute. While the Newtonian mechanics gives flawless results for these concepts at low speeds, a radical change is observed as we get closer to the speed of light. The results of these postulates cannot be observed in everyday life since we do not often encounter objects moving at speeds close to the speed of light.

Today, the value of the speed of light has been determined with great accuracy (approximately 3.10^8 m/s). This value is the same in all reference systems as proven by the results obtained by Michelson and Morley. It is also independent from the source of light. The speed of light (c) is one of the basic constants of modern physics. Therefore, studies first conducted 300 years ago to determine the value of the speed of light more precisely still continue today (Shivalingaswamy & Rashmi, 2014).

The theory of special relativity suggests that the unbeatable speed limit for objects is the speed of light. Therefore, the upper limit for all movements in the universe is accepted to be the speed of light. For these reasons, the foundation of special relativity and quantum physics is to understand the concept of the speed of light. This theory, which revolutionized the era in which it was published, has become an indispensable part of the universe's science and particle physics studies. For these reasons, quantum physics and special relativity were first included in the university curriculum, then in the high school physics curriculum. It has been argued that special relativity should also be taught at secondary school (Fabri, 2005; Levrini, 2002; Otero, Arlego & Prodanoff, 2016; Otero & Arlego, 2018; Perez & Solbes, 2003) and at the end of primary school (Astin, 2005) in some studies. However, the learning process of this theory is far from daily life experiences, and understanding its effects causes some concerns in learners (Perez & Solbes, 2003; Toledo, Arriasseco & Santos, 1997). Students may find this theory to be more relevant than topics of everyday practical use, such as electricity or friction (Henriksen, Bungum, Angell, Tellefsen, Fragat, & Bøe, 2014).

A review of the literature reveals that the speed of light is usually addressed in studies investigating the nature of light. In these studies, students are usually asked questions regarding those aspects of light and the speed of light that can be observed in everyday life (Bendall, Galili & Goldberg,

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https://doi.org/10.12973/ijpce/713687

1993; Cansungu, 2000; Galili & Hazan, 2000; Heywood, 2005; Kara, Avci & Cekbas, 2008; Langley, Ronen & Eylon, 1997; Popov, Zackrisson & Olofsson, 2001; Sen 2003; Van Zee, Hammer, Roy & Peter, 2005; Yildiz, 2000).

It is seen that the property of speed of light is included in the lower dimensions of studies on special relativity. However, it is also observed that these studies mainly focus on examining the concepts of simultaneity, reference system, and time (De Hosson, Kermen & Parizot, 2010; Scherr, Shaffer & Vokos, 2001; Ozcan & Abak, 2007**;** Sezgin Selçuk, 2011). In their study investigating how students comprehend special relativity, Dimitriadi and Halkia (2012) found that students had difficulties in comprehending the invariance of speed of light, which is the 2nd postulate of special relativity. They concluded that this condition constituted an impediment in understanding special relativity. Considering the findings of studies which examine the difficulties experienced by students in relation to special relativity, it was observed that students had difficulties in understanding the invariance of light velocity (Villani & Arruda, 1998). In some studies, on the other hand, it was found that students had the knowledge that "speed of light is invariable" (Arlego & Otero, 2017; Korkmaz, Aybek & Orucu, 2016; Scherr et. al., 2001; Turgut, Gurbuz, Salar & Toman, 2013); however, they had difficulty in applying this knowledge to problems and other concepts (Dimitriadi & Halkia, 2012; Gousopoulos, Kapotis & Kalkanis, 2016; Korkmaz, Aybek & Orucu, 2016; Pietrocola & Zylbersztajn, 1999; Scherr et. al., 2002).

There was a very limited number of studies investigating the concept of light velocity, which is the basis of special relativity. This study will contribute to the literature by attempting to seek an answer to the following questions:

- How are the concept structures of prospective physics teachers regarding speed of light?
- Which concepts do prospective physics teachers connect with the concept of speed of light?
- Which features of the speed of light do prospective physics teachers know?

Studies on special relativity use open-ended questions (Dimitriadi, Halkia & Skordoulis, 2004; Guisasola, Solbes, Barragues, Morentin & Moreno, 2009; Scherr et. al., 2002; Turgut et al., 2013), clinical interviews (Dimitriadi & Halkia, 2012; Korkmaz, Aybek & Orucu, 2016; Pietrocola & Zylbersztajn, 1999), multiple choice questions (Aslanides & Savage, 2013; Korkmaz, Aybek & Orucu, 2016), concept cartoon (Kandil-İngeç, 2016), four-step concept misconceptions test (Onsal, 2015), and drawing-based questions (Arlego & Otero, 2017; Otero, Arlego & Prodanoff, 2016; Popov et. al., 2001) as data collection tools. In this study, we used concept maps as a different data collection tool in order to investigate how prospective teachers understand the concept of speed of light. Thus, we believe that in the minds of prospective teachers, the relation between the concepts can be seen more clearly.

Concept Maps

Concept maps are based on learning theories of Ausubel (Ausubel, 1968, 2000) and Novak (Novak & Gowin, 1984). Concept maps are two-dimensional, hierarchical, and graphical representations of relations between concepts in the cognitive structure (Horton, McConney, Gallo, Woods, Senn & Hamelin, 1993; Martinez, Perez, Suero & Pardo, 2013; Quinn, Mintzes & Laws, 2004).

Concept maps are an important way to help researchers focus on understanding in qualitative research. The data can be used to simplify and identify categories and links between concepts using concept maps (Daley, 2004). They have been used extensively for developing higher order thinking skills (Heron, Kinchin & Medland, 2018). Concept maps remain an integral part of the data analysis process because they illustrate similarities and differences between concepts and how concepts are classified (Novak & Gowin, 1984).

Concept maps have different areas of use in physics teaching. Concept maps have been used to examine students' prior knowledge (Montanero & Montanero, 1995), as study materials (Dorough & Rye, 1997; Senthilkumar, 2017; Zieneddine & Abd-El-Khalick, 2001), in the process of learning (Martinez et. al. 2013; Novak 1998; Patterson, Dansereau & Newbern, 1992; Perez, Suero, Pardo & Montanero, 2006; Slotte & Lonka 1999; Stoyanova & Kommers 2002), and to solve physics problems (Austin & Shone, 1995). They have also been used as assessment and evaluation tools (Kandil-İngeç, 2008; Kandil-İngeç, 2009; Eroglu & Kelecioglu, 2011; Ruiz-Primo, 2004; Sen & Aykutlu, 2008; Walker & King, 2003; Won, Krabbe, Ley, Treagust, & Fischer, 2017).

Method

Document analysis, which is a qualitative research method, was used to obtain research data in order to investigate the concept structures of prospective physics teachers regarding the concept of speed of light. In the study, a group of prospective physics teachers were asked to draw concept maps regarding special relativity from which information about the concept structures of speed of light were collected.

Study Group

The study was conducted with a group that was selected from prospective teachers studying in the physics teaching program of a state university in spring semester of 2014-2015 academic year. Over five years this program involved both physics and education courses. Special relativity is taught to prospective teachers in the 3rd year of the program within the scope of the quantum physics course. Students who graduate from this program will be able to work at public high schools and teach physics subjects including special relativity to high school students. Thus, it is important for them to comprehend special relativity accurately.

The study group was determined by using the criterion sampling method, which is one of purposeful sampling methods. Criterion sampling is the formation of the sample with individuals, events, objects or conditions that have the qualities determined regarding the problem (Yildirim & Simsek, 2008). The basic criterion for determining the study group is that participants should have information about special relativity and concept maps. Accordingly, this study investigated prospective teachers who had studied the quantum physics course which teaches special relativity. Forty-six prospective physics teachers (30 females, 16 males) who had the required qualities, and were studying in the 4th and the 5th grade of the course constituted the study group.

As a result of some studies, it has been determined that Turkish students have difficulties in drawing concept maps since the Turkish sentence structure is ordered as subject-object-verb. Concept maps are briefly introduced in the special teaching methods course in the physics teaching curriculum. Thus, not all prospective teachers in the curriculum are experienced in drawing concept maps. It is important for prospective teachers to be experienced in drawing concept maps in order to avoid problems that would be caused by the structure of language. Prospective teachers that had detailed information about concept maps and were experienced in drawing concept maps on various physics subjects were included in the study group. The experience of prospective teachers in drawing concept maps were categorized as "1-3 times", "4-6 times", "7 times and more", which is presented in **Figure 1**.

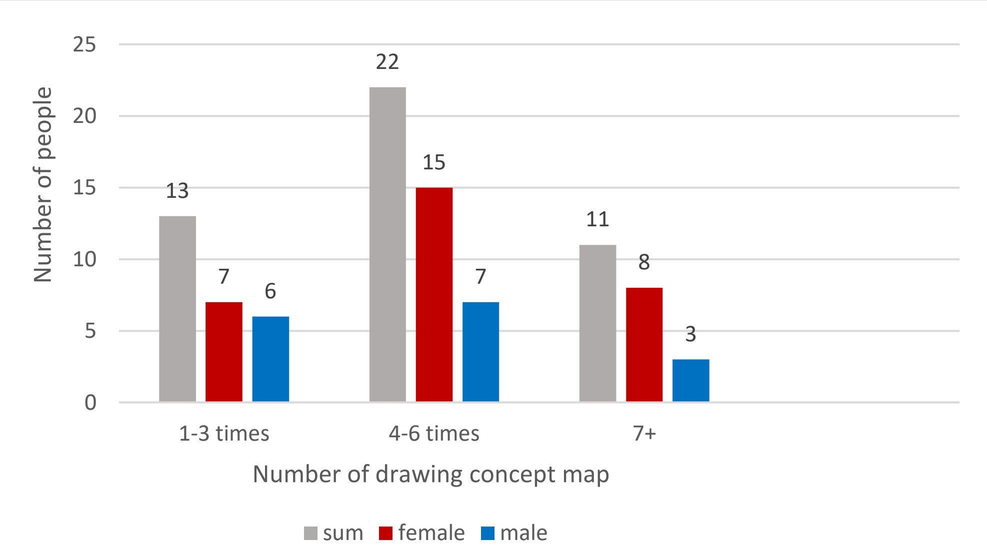

Figure 1. Experiences of prospective teachers in drawing concept maps

Data Collection

The low-directed (construct-the-map) technique in which the students can build their own sentences was used. In a low-directed concept map task, students are free to decide which and how many concepts they include in their maps, which concepts are related, and which words to use to explain a relationship (Ruiz-Primo, 2004). The low-directed technique provide students with more opportunities to reflect their actual conceptual understanding (Ruiz-Primo et al., 1996). It seems to be a relevant method for addressing students' individual prior knowledge as it is low-directed, allowing non-restricted individual knowledge to be included; hence, this type of mapping has high validity for exploring students' individual knowledge and understanding (Hartmeyer, Bølling, & Bentsen, 2017). The low-directed concept mapping technique is also believed to provide students with the opportunity to develop their creative and critical thinking skills (Ghani, Ibrahim, Yahaya & Surif, 2017). Prior to the implementation, 16 concepts related to special relativity were determined with the help of two experts. A list of these concepts was given to the prospective teachers and they were asked to create concept maps for special relativity. The prospective teachers were asked to create concept maps for special relativity only by relying on their own knowledge with these concepts and not using any other sources. The prospective teachers were told that they did not have to use all concepts in the list and were free to add other concepts if they wanted to. Links to light velocity were determined by individually examining the 46 concept maps, which were constructed using a low-directed technique.

The maps were evaluated according to the Novak-Gowin, totality and relational scoring techniques. Resolutions written for the concept of light velocity were deciphered by the opinions of two expert. Meaningful proposals were chosen among the resolutions and listed as propositions.

Data Analysis

Content analysis and the open approach technique were used for data analysis. The main purpose of the content analysis was to obtain relationships that could explain the data. The data were gathered under similar themes, organized in a way that they could be understood and interpreted by the reader (Yildirim & Simsek, 2008). In the determination of the proposition categories, the open approach technique was used, in which items were divided into categories according to their similarities and differences without using predetermined categories (Henry & Moscovici, 1968). First of all, all propositions were read. Propositions were grouped according to their meanings and themes (categories). Each theme was divided into sub-themes according to similarities between propositions. The propositions were placed under sub-themes. The opinions of a second expert were considered regarding themes and sub-themes.

Validity and Reliability of the Data

In content analysis, the validity is about ensuring that messages reach the target without deterioration. Reliability, on the other hand, depends on the encoding process. It requires different coders to encode the same message in the same manner (Bilgin, 2000). Due care was taken to clearly show how the study results were obtained in order to improve the internal validity of the study. The resulting data were systematically presented and those examples of propositions belonging to prospective teachers which were found to reflect the subject best were given as is, without comments. In order to improve the external validity of the study, steps followed in the study, the data collection, data analysis and data interpreting processes were explained in detail.

In order to improve the reliability of the study, due care was taken to decrease the researcher-induced error and bias ratio and to ensure that codes represented themes accurately. To ensure this, propositions written by prospective teachers were encoded by two experts and codes obtained from the experts were compared. The following formula suggested by Miles and Hubermann (1994) was used to calculate the reliability between the experts: (Reliability = Consensus / [Consensus + Divergence]). An initial consensus of 96% was found as a result of this operation. Experts came together and discussed until a 100% consensus was reached on the resulting table. In addition, the research data were archived so that it could be exported to other researchers if requested.

In addition to this consensus, in order to improve the reliability of the study, the data were scored by three different methods: Novak-Gowin, totality, and relational scoring techniques. The average of these scores was evaluated as the concept map notation. The correlation belongs to the obtained scores of concept maps was calculated and shown in **Table 1**.

Table 1. The correlation belongs to the scores of concept maps

	Novak-Gowin	Totality	Relational
Novak-Gowin	1,000		
Totality	,395 (382)**	1,000	
Relational	,694**	,559 (601)**	1,000

Pearson correlation coefficient is calculated. $n = 46$, $^{**}p < .01$

Table 2. Descriptive statistical results

	N	Min	Max	S
Novak-Gowin	46	87	17	55
Totality	46	12	7	12
Relational	46	19,75	2,67	10,96

As shown in **Table 1**, there is a positive relationship between scores of concept maps. Pearson's correlation coefficient was 0.4, 0.7, 0.6, meaning a significant, moderate and high correlation was found. Descriptive statistical results are presented in **Table 2**.

Findings

Examining the maps considering the concept of speed of light, it was found that prospective teachers established relations between 21 concepts concerning speed of light. These concepts are light (*f*=24), Newtonian mechanics (*f*=13), time (6), photon (*f*=6), mass (*f*=12), special relativity (*f*=18), reference system (*f*=2), Lorentz transformations (*f*=6), non-inertial reference system (*f*=2), inertial reference system (*f*=4), mass-energy equivalence (*f*=1), Galilean transformations (*f*=1), quantum mechanics (*f*=2), energy (*f*=3), relative momentum (*f*=1), twin paradox (*f*=3), relative energy (*f*=2), relative mass (*f*=2), length (*f*=3), length contraction (*f*=6), and time dilation (*f*=6). Being included in twenty-four concept maps, light had the highest frequency. It was identified that there were propositions such as "light moves at the speed of light", "the speed of light is related to light", and "the speed of light is the speed at which light travels through space". The concept with the second highest frequency was special relativity. Special relativity and speed of light were associated as "the special relativity is valid at speeds higher than the speed of light", and "the special relativity investigates speeds close to the speed of light". The links prospective teachers make for the concept of speed of light are shown in **Figure 2**.

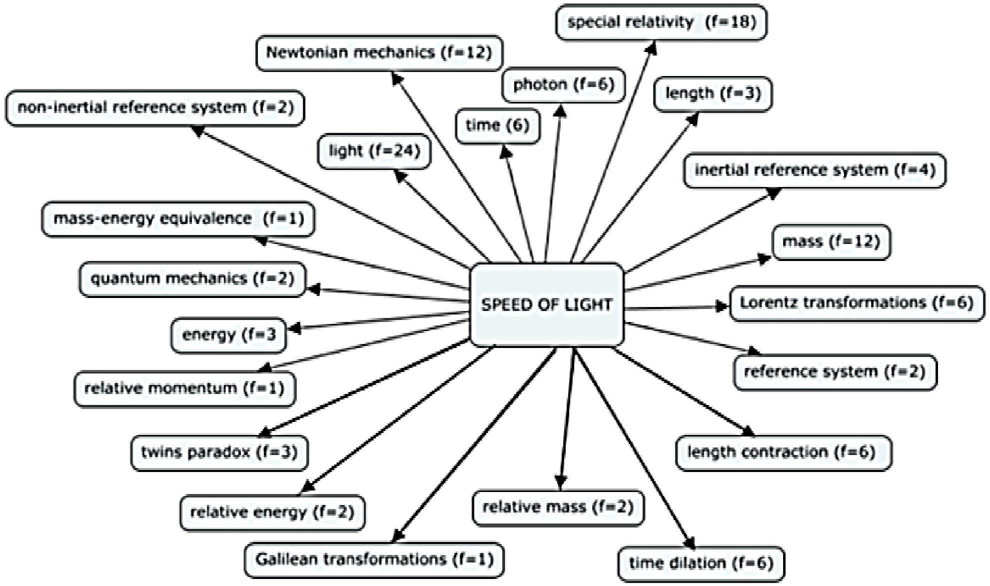

Figure 2. Physics prospective teachers established relations regarding speed of light concepts

Examining concept maps created by prospective teachers about the concept of the speed of light, a total of 77 propositions were found in the 46 maps. As a result of the content analysis, four 4 themes were determined for these propositions. The main themes were the effect of the speed of light, exemplification, the constancy of the speed of light and the property of the speed of light. These categories were divided into 19 sub-themes into which the propositions were placed. The themes, sub-themes, the number of concept maps involving themes and the distribution of propositions according to themes are given in **Table 3** below.

Table 3. Themes and sub-themes related to the speed of light and the distribution of propositions

Themes	The number of prospective teachers who used the theme	The number of propositions under the theme	Sub-themes	The number of propositions under the sub-theme	Examples of student propositions
The effect of the speed of light.	17	38	Time dilation	15	*Time dilation occurs approaching the speed of light.*
			Length contraction	13	*Length contraction occurs when an object moves at a speed close to the speed of light.*
			The twin paradox	4	*The underlying reason of the twin paradox is the speed of light.*
			Energy	2	*If an object reaches the speed of light, it becomes energy.*
			Relative momentum	2	*If a stagnant mass moves at the speed of light, a change in momentum is observed.*
Exemplification	21	22	Light	14	*The speed of light is the speed at which light propagates in space.*
			Photon	8	*Photon travels at the speed of light.*
The constancy of the speed of light	7	12	In an inertial reference system	3	*The speed of light is constant in inertial reference system.*
			In special relativity	2	*It is accepted in special relativity that the speed of light does not change.*
			In a non-inertial reference system	1	*It is accepted in non-inertial reference system that the speed of light does not change.*
			Independence	2	*The speed of light is independent from the reference system.*
			Dependence	2	*The speed of light is affected by non-inertial reference system.*
The property of the speed of light	7	9	The highest speed.	1	*Special relativity accepts that the speed of light is the highest speed.*
			The higher speed.	8	*Relative energy applies at higher speeds than the speed of light.*

Table 3 shows that the highest number of propositions were written under the effect of the speed of light theme (38/117), which is one of the results of the theory of special relativity. Considering sub-themes, time dilation (15/117) and length contraction (13/117) had the highest number of propositions. Although there were 15 propositions under the time dilation sub-theme, the number of propositions written under the twin paradox sub-theme (4/117) was low. In addition, although the effect of the speed of light was the category with the highest number of propositions, 63% of the prospective teachers (29/117) did not write any propositions under this category.

It was seen that prospective teachers mentioned the concepts of photon and light as examples regarding the speed of light. Thirty percent of the concept maps (14/117) included the proposition "Light travels at the speed of light.", while 17% (8/117) involved the proposition "Photon travels at the speed of light". There was one prospective teacher who indicated that the speed of light was the speed at which light propagates in space. As many as 54% of the prospective teachers (25/117) did not write any propositions under this category.

Only 15% of the prospective teachers (7/117) wrote a proposition under the constancy of the speed of light category. In this category, prospective teachers stated that the speed of light was constant in a non-inertial reference system (3/117), in special relativity (2/117) and in an inertial reference system (1/117). Only two prospective teachers (4%) indicated that the speed of light was independent from the reference system. On the other hand, two prospective teachers (4%) stated that the speed of light depended on the reference system.

The property of the speed of light category was mentioned by 15% of the prospective teachers (7/117). Only one concept map (2%) included the most significant property of the speed of light, which is the fact that it is "the highest speed". On the other hand, eight prospective teachers (17%) indicated that there were higher speeds than the speed of light. Two prospective teachers (4%) indicated that the speed of light was directly proportional to energy.

Discussion and Conclusion

The main themes obtained by deciphering the concept maps were the effect of the speed of light, exemplification, the constancy of the speed of light, the property of the speed of light, the scope of the speed of light and transformation equations. A total of four themes and 14 sub-themes were found.

It could be suggested that the theme of the "effect of light velocity" is perceived as time expansion, length contraction, twin paradox, energy, and relativistic momentum by the participants. Prospective teachers mainly wrote resolutions in the category of the effect of light velocity. Resolutions written in that category were mainly observed in the sub-categories of time expansion and length contraction. Another point that attracts attention is that even though time expansion was mentioned by most, the twin paradox which is an example of time expansion was mentioned only by four prospective teachers. This situation may signify the presence of a problem in associating the example of the twin paradox with the concepts of light velocity and time expansion.

A total of 22 resolutions were written under the theme of “Sampling”. This theme comprised of the sub-themes of “photon” and “light”. Prospective teachers wrote resolutions suggesting that photons (8/22) and light (14/22) moved with light velocity. The formation of this theme and sub-themes was an expected result. Accordingly, it could be suggested that prospective teachers have information about the nature of light.

The theme of the “invariance of light velocity” comprises five sub-themes as “inactive reference system”, “special relativity”, “active reference system”, “independence” and “dependence” and 12 resolutions. This finding shows that prospective teachers embraced light velocity according to active or inactive reference systems and its examination within the context of special relativity. However, in the sub-theme of “dependence” (2/12), it was stated that light velocity was affected by the reference system. In the sub-theme of “independence”, on the other hand, it involved a very limited number of resolutions (2/12). From a general glance, the statement regarding the invariance of light velocity was encountered in only 2 of 77 resolutions written by prospective teachers. It also became clear that although the prospective teachers have knowledge on the topic, they have difficulty establishing relationships among the invariance of light velocity. Consequently, this investigation has identified difficulties that prospective teachers are unable to comprehend the invariance of light velocity. This finding is highly important. In the literature, there are studies which show that students are unable to comprehend the invariance of light velocity. Dimitriadi and Halkia (2012) identified similar difficulty. In their study investigating the comprehension of special relativity, Dimitriadi and Halkia (2012) determined that students had difficulty in comprehending the invariance of light velocity, which is the 2nd postulate of special relativity. They concluded that this condition constituted an impediment in comprehending special relativity. It is one of the problems in learning special relativity. According to some studies (Gousopoulos, Kapotis, and Kalkanis, 2015; Scherr et al., 2002), on the other hand, regarding the second postulate, students accept the invariance of the light speed. It was determined that students had the knowledge that “the speed of light is the same in all directions in all reference frames.”; however, they had difficulty in applying this knowledge to problems and other concepts. As emphasised by Scherr, Shaffer and Stamatis (2002), most students can state that the speed of light is the same in all directions in all reference frames, however, few students have the ability to use this knowledge to analyze relativistic scenarios. As stated by Gousopoulos et al. (2015), many students stated correctly the invariance of the speed of light, but they failed to apply it in problems in which the speed of light was demanded. According to Otero, Arlego and Prodanoff (2016), the light speed is very large value, compared with low speed everyday experience, we detect the use of the theorem-in-action: “the light is instantaneous”. Regarding the idea that light propagates instantaneously, the use of equations of motion to solve meeting point problems brings the possibility of direct application of the invariance of light and thus the prediction of lack of simultaneity.

The results of this study differ from the aforementioned studies. In their study on light velocity, Bendall et al. (1993) concluded that students were unable to realize the invariance of light velocity as it could not be comprehended with sensorial experiences. It was stated that students had that knowledge simply because it was written in the book. The acquired findings match with the interpretation of Bendall et al. (1993).

In the study, the 4th theme of the “property of light velocity” comprises two sub-themes as “largest velocity” and “larger velocity” and nine resolutions. The presence of the sub-theme of “larger velocity” is another highly interesting result. In this sub-category statements by eight prospective teachers suggest that there are velocities larger than light velocity. This finding may signify that there is a problem in comprehending the second postulate of relativity. As a result of some studies in the literature, it may be concluded that students knew that light velocity had an end, but the non-exceedance of light velocity was a technological problem and the progress of technology could enable larger velocities. This result might be explained with the interpretation of Galili and Hazan (2000), who suggest that important obstacles in learning are caused by students’ concretization of light in their mind.

Suggestions

The 2nd postulate of special relativity suggests that light velocity is the largest velocity that could be reached and it has an invariance value. Dimitriadi, Halkia and Skordoulis (2004) emphasize the importance of the key concepts of light velocity and reference system in teaching special relativity. It cannot be expected to comprehend the subject of special relativity without comprehending these two basic properties of light velocity. It is very important to primarily emphasize the reference system of light velocity, its independence from the role of the observer and its acceptance as the largest velocity. It is recommended that other concepts are not taught without fully comprehending the concept of light velocity in the teaching of special relativity.

The properties of light velocity whose concrete examples are not frequently encountered in daily life could be concretized with thought experiments in the classroom environment. Students’ interactive brainstorming aimed at solving a problem might make the subject more understandable. Teaching special relativity with thought experiments also gives efficient results.

Zhang (2005) developed a module containing problem-based learning and case study for the teaching of special relativity. Similarly, there are developed modules for teaching special relativity (Aragoneses, Salán Ballesteros & Hernández Fernández, 2017; Henriksen et al, 2014; Otero, Arlego & Prodanoff, 2016; Stannard, 2018). The application of these modules have given positive results. It is recommended to develop similar modules as the modules for the concept of light velocity.

As a result of his study examining school books of high school students, Gim (2016) claimed that science history was effective in comprehending the postulates of special relativity. Thus, giving a place to science history may also be effective in comprehending the postulates of relativity in the teaching of special relativity.

This study examined how prospective physics teachers comprehend the concept of light velocity, which is one of the basic concepts of special relativity and tries to reveal relevant problems. It is also recommended to investigate how other concepts of special relativity are comprehended and reveal the difficulties experienced by students in other concepts in the learning of special relativity.

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