Students’ Understanding of the Special Theory of Relativity and Design for a Guided Visit to a Science Museum

Jenaro Guisasola[a]*, Jordi Solbes[b], José-Ignacio Barragues[a], Maite Morentin[a] and Antonio Moreno[c]
[a]Universidad del País Vasco, Spain; [b]Universidad de Valencia, Spain; [c]Universidad Complutense de Madrid, Madrid, Spain

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The present paper describes the design of teaching materials that are used as learning tools in school visits to a science museum. An exhibition on ‘A century of the Special Theory of Relativity’, in the Kutxaespacio Science Museum, in San Sebastian, Spain, was used to design a visit for first- year engineering students at the university and assess the learning that was achieved. The first part of the paper presents the teaching sequence that was designed to build a bridge between formal teaching and the exhibition visit. The second part analyses the potential of the exhibition and the aforementioned teaching sequence to influence the students’ knowledge of three aspects of the Special Theory of Relativity. The results obtained show that the design of the visit, with both pre- visit and follow-up activities, was effective as a means of increasing students’ understanding and stimulating their ability to argue scientifically.

Introduction

In the present paper we describe the curricula design used as a learning tool in school visits to a science museum. Learning in informal contexts and ‘experience outside the classroom’ is being recommended as an important element to promote interest in sciences and their learning, and to encourage student motivation (Pedretti, 2002). Visits to science museums represent one such type of these activities and they are used as part of the proposal to increase scientific literacy in both the student population and the wider adult population. However, the results of research into the use of science museums as learning instruments for school children indicate that teachers generally establish very general, or limited, objectives for the museum visit—mainly restricted to relating science to the social medium, or developing a practical science activity already undertaken in class (Griffin & Symington, 1997); that generally there is usually very little preparation for the visit and little monitoring of the actual visit in the museum, although the majority of research highlights the positive effects of good visit preparation on student learning and attitude (Falk & Dierking, 2000; Gennaro, 1981); and that the importance of interaction between the students, and between students and the teacher, is highlighted (Hofstein & Rosenfeld, 1996).

Educators and researchers are interested in how to develop the role of science museums in supporting school-based learning. This interest is illustrated by the increasing number of research projects on the interface between school curriculum and museum visits. Different studies have shown that visits to museums and science exhibitions, organized with activities to carry out during the visit and supported by appropriate prior and post-visit activities to discuss in the classroom, can consider- ably increase student interest and knowledge (Anderson, Lucas, & Ginns, 2000; Henriksen & Jorde, 2001). Taking these findings into account, in this study we designed educational materials to improve learning in the school-museum learning context and to aim to incorporate the students' own questions, or topics, which have been previously analyzed in class. This aims to ensure that students have an under- standing of the information supplied by the museum, within the previously decided parameters, and to promote critical analysis of the ideas resulting from the visit and the application of these ideas to new situations.

This paper looks at teaching the topic of the Special Theory of Relativity (STR) in a seminar for first-year engineering students (students aged 18–19 years), which included a visit to the 'A Century of the Special Theory of Relativity 1905–2005' exhibition. The exhibition was held in the Kutxaespacio Science Museum, in San Sebastian, Spain, with collaboration from the University of the Basque Country (Guisasola, Peñalba, Barragués, Moreno A, & Ares, 2005), and its objective was to provide intelligible and contextualized scientific information on the fundaments of the STR and its technological and social implications. The central topics of the exhibition were:

- The speed with which we can transmit information.
- Reference systems: simultaneity of events and measuring time.
- The problem of the limit of the speed of light.
- The origin of nuclear energy.

The exhibition designers' intention was to help visitors, particularly groups of students over 15 years old, to use a scientific base to generate their own opinions and arguments related to topics in telecommunications and nuclear energy (Guisasola et al., 2005). The exhibition included computers simulations that visitors can manipulate, including a reconstruction of the famous experiment by Michelson and Morley and explanatory panels. The panels use situations with which visitors are likely to be familiar with to capture their attention and they use analogies to explain the scientific principles.

The present paper is centred on the design of the teaching sequence that uses visits to the exhibition 'A Century of the Special Theory of Relativity 1905–2005' as part of an instructional approach that seeks to improve understanding of the STR. We tried to answer the following research questions:

- What type of prior conceptions do the students have of the Special Theory of Relativity and its applications?
- How does the museum visit influence students understanding of the Special theory of Relativity and its applications? Does the students' understanding of this theory increase? Do students use more scientific arguments when discussing topics related to the Special theory of Relativity after visiting the exhibition?

The exhibition was the result of collaboration between a team of lecturers from the University of the Basque Country and the curators of the museum. It is neces- sary to state that selection of the problems covered in the exhibition (mentioned in the previous paragraph) was proposed by the faculty team from the University of the Basque Country. This selection of problems and contents was based on three criteria. Firstly, a description of the scientific context in which Einstein began his research and the scientific problems that he tackled, as well as the solutions (the STR) that he eventually devised. Secondly, an increase in interest and knowledge of the STR, centred on technological applications of the STR that can most impinge on the everyday life of ordinary citizens. Thirdly, it was based upon the results of the investigation into students' alternative ideas about the STR.

This was not a standard exhibition put together by the museum staff; nor was it outsourced to a company specializing in museum services, but rather to a faculty team from the University of the Basque Country, which conducts research into science education, had the opportunity to design the exhibition from the start, and conceived the content of the labelling, panels, and the form of the presentation.

Experimental Design

Sample

A total of 35 students (63% male and 37 % female) in the first-year engineering course participated in the experiment. These students study general physics at university and they also studied physics for 1.5 years after they graduated from secondary education. However, they have not covered the STR in any of the physics courses they have taken and nor is it planned that they will acquire knowledge on this topic within the course.

The students were chosen from a class given by a teacher who had worked on the 'A Century of the Special Theory of Relativity 1905–2005' exhibition in the Kutxaespacio Science Museum. These students took a 4-hour seminar at university and visited the exhibition. As the experiment is not included in the official course programme, we can assume that the teacher was probably more than normally involved in motivating the students and presenting relevant activities.

Teaching Sequence

When designing the teaching sequence, we based it on the 'contextual model of learn- ing' by Falk and Dierking (1992, 2000), which incorporates many elements of what we know about learning. The model looks at multiple contexts, creating a useful framework to analyze the nature of learning, specifically in the non-school environment. It is emphasized that learning occurs in a context and that, in the absence of any external direction, each individual's associations can be insignificant. Learning is not an experience that is carried out in abstract, but in a specific situation in the real world—combining personal, socio-cultural, and physical aspects. Visitors to a museum are considered people who are actively involved in constructing and recon- strutting knowledge. The model is intentionally more descriptive than predictive.

In the sequence we are presenting, a teaching unit has been designed and put into practice to act as a bridge between the school context and the museum context. For this purpose, activities were designed for 'before', 'during', and 'after' the visit, which provide a unifying sequence for the different contexts in which the students will learn. Furthermore, the type of activities have been designed taking into account the possibilities that are offered by each situation in school and in the museum. So, the pre-visit and post-visit activities are based more on analyzing and discussing carefully selected situations involving STR, whilst the activities in the museum aim to provide students with an opportunity to experiment, provide meaning and interest to the questions raised, and let them search for information.

The teaching unit used as a research instrument in this work is summarized below.

Pre-visit activities (2 hours). The teacher explains (10 minutes) that the objective of the seminar involves understanding the basis of the STR. Firstly, the students individually fill in a questionnaire on their understanding of STR and its social implications (30 minutes). These topics are later covered in the pre-visit seminar. Once the questionnaire has been completed, a debate is started on the four situations that have been designed: 'Telecommunications', 'Your seconds are longer than mine', 'Are muons young or old?', and 'Experiment in the [CERN Conseil Européen pour la Recherche Nucléaire (European organization for the Nuclear Research)]'. Different opinions are expressed on the situations that have been presented. The situations presented follow the sequence that will later be seen in the exhibition, which we can summarize in the following way:

- 'Telecommunications': Is it possible to transmit information increasingly rapidly? Is this problem related to the STR?
- 'Your seconds are longer than mine': Galileo and relative movement. Is it possible that a phenomenon lasts for a different time depending on where we observe it from? Is the speed of light of a torch faster in a high speed rocket than outside the rocket at rest?
- 'Are muons young or old?': A practical example of different time measurements for the same phenomenon.

‘Experiment in CERN’: Does increasing the force applied to a body always give greater acceleration? What does the famous equation $E = mc^2$ mean? Does it have any relation to nuclear energy?

The first of the situations, introducing problems related to the speed of light and electromagnetic waves, is presented below.

> Story 1: Telecommunications
>
> Imagine a heart operation, or an organ transplant carried out between Osakidetza in Bilbao and a Hospital in Quito in Ecuador. For the operation to be successful, it is vital for the information to arrive via video conference (electromagnetic waves) in the shortest possible time and in the greatest possible quantity. This is not science fiction, in 2001 the first operation was carried out with transoceanic telesurgery. A team of experts from the European Telesurgery Institute in France carried out an operation from New York, on a 68 year old patient located in Strasbourg. Two surgeons drove the robots from New York, whilst the other two experts in Strasburg were in charge of controlling the computer system.
>
> The information travelled 14,000 km, from its point of origin in the United States to its destination in France. Due to the time which the information took to cover this distance and the coding period for the data on video, the movements of the surgeons appear on the TV monitors with a delay of 155 milliseconds, ‘a time which lies within the safety margins, which estimate 330 milliseconds as a maximum,’ said the team.
>
> The electromagnetic waves which transport the information take a certain time to travel from one place to another. Also light, which is an electromagnetic wave, takes a certain time to travel from one point to another.
>
> The possibilities provided by communication at increasing speeds are growing and we are already talking about a ‘global world’ and the enormous efficiency of new information technologies.
>
> Do you believe that it is possible that the time will come when communication occurs instantaneously? Explain your opinion.

Students were organized into groups of four. They first read the information individually, and then discuss and answer the problem in groups. Before work-groups start answering the questions, the teacher explains, with examples, how evidence is used to support scientific explanations; they need to be able to evaluate evidence in terms of its adequacy, its relevance, and its source. The teacher explains that, as will be seen in the visit to museum, scientific explanations can draw on a range of evidence—in the form of numerical data, recording of observations, or other established scientific facts—so there is a need to explore different ways to justify their ideas and conclusions.

When students are working in groups, the teacher takes a backseat, supervising the students, because students need time to think for themselves and to clarify their ideas. When the students have finished their work, there is a roundtable discussion, directed by the teacher. At the roundtable, each group must justify the answers at which they arrive. Ultimately, there will be one or several explanations for each problem. The teacher will insist that every explanation must be justified by evidence, or scientific arguments (Guisasola, Furió, & Ceberio, 2008).

Visit to the museum (1 hour 30 minutes). The visit took place two days after the pre-visit activities. The teacher and the students meet in the entrance hall and are shown the different parts of the museum on the map (rooms, panels, leisure areas, planetarium, etc.). The teacher and the students walk together from the entrance hall to the exhibition room for ‘A Century of The Special Theory of Relativity’ of the Museum; the teacher asks them to look around and see the different ways in which information is given. They can see interactive panels, real experiments, computer simulations, and multimedia presentations. The teacher reminds them about the work they have done beforehand at university and how it can help them to centre themselves on the information they want to obtain in order to resolve the questions posed in class. The students review the notes they took in the class discussion and the map of the exhibition.

The students divide themselves up into small work groups (four people in each) that were established during the class discussion. One of the members of the group, who acts as secretary, carries a notebook and pencil—another member of the group could carry a video camera to illustrate the group’s conclusions later. The students use a guidebook designed to direct the students towards the information they need to look for in relation to the questions covered in the pre-visit activities. In the example we show, the process will be as follows.

> *Guide book (What has happened?)*: In the ‘controlling a robot from the Earth’ simulation, read the panel information and then try to guide the robot to a certain point on a planet that has been chosen (Mercury, Venus or Mars). Does it take the same amount of time for the commands to reach the robot on each of the three planets? What determines the amount of time that it takes for the commands to reach the robot? Why do the commands take time to reach the robot?
>
> *Simulation panel*: From Earth, you will command the movement of a robot on one of three planets that you choose: a) Mercury; b) Venus; c) Mars. Mercury is 82 million kilometres away from Earth, and light takes 2.2 minutes to cover this distance. Venus is 40 million kilometers away from Earth, and light takes 1.07 minutes to cover this distance. Mars is 56 million kilometers away from Earth, and light takes 1.5 minutes to cover this distance’.
>
> *Exhibition information panel (located close to the simulation)*: Electromagnetic waves, which transport information, require time to travel from one point to another. Like any other electromagnetic wave, the speed of light in a vacuum travels at 300,000 Km/s. Light therefore requires a certain amount of time to travel from one point to another, although due to its speed the distance must be very great in order to note it. As you can see from the simulation, at distances as great as those from Earth to Mars, commands sent from Earth Control Centre to the robot will take several minutes to arrive, and problems may arise when trying to control the robot.
>
> Information transmission speed is key in the Communications and Information Society in which we live. Therefore, scientists and society have asked themselves: Is it possible to induce electromagnetic waves to travel faster than 300,000 Km/s?

The students are free to move around the exhibition. The teacher asks the students about the reasons for choosing one exhibit or another and how the work is progressing. The teacher moves between the different work groups showing interest in the students' activities, and asks them questions that stimulate them to look in greater depth at the information given by the panels and to answer the questions previously posed in class.

After about an hour, the students start to go to the museum's leisure area for a 10-minute break. They can chat with other groups there about the information they have found and the progress they have made regarding the questions they brought with them. Then they will go back to the exhibition and programmed exhibits together to finish their research.

After 1.5 hours, the teacher reminds the group that it is time to return to the bus.
The students will have been handling interactive exhibits and taking notes from informative panels or filling in their notebook. They are prepared to show the information they have found and answer any questions that emerge in the later session in the university.

Post-visit activities (2 hours). These activities were run in class in the week following the visit. In groups, the students reflected on the information and the experiences from the visit and whether their knowledge on the topic had changed regarding the pre-visit questionnaire. Later, they individually had to produce a final report, which, among other questions, centred on the following aspects of STR:

1. Is it possible to transmit information at a speed that is greater than the speed of light? Have we reached the maximum speed for communications?
2. Can the same phenomenon last for different times depending on where it is observed from? Give an example and justify it.
3. Why is the speed of light the maximum possible in our universe? If we push an object with sufficient of force, couldn't we exceed this speed?
4. What is the relationship between mass and energy at very high speeds? Give an example and comment on it.

At the end of the session, the teacher takes the initiative in discussing and reformu- lating relevant information from the activities and experiments. In this process, students must propose well-founded hypotheses and justify the approach that leads them towards a specific explanatory theory.

Methodology

It must be highlighted that the experimental design does not consist of the usual pre- test/post-test design, as the very instrument of research (the teaching unit) is part of the treatment. So then, a difference that is observed between the pre-test and post- test results, which is interpreted as a change in the students' understanding, can be attributed not only to the visit to the museum, but rather to the overall pre-visit, visit, and post-visit teaching process. The design of the experiment is based on results from other research into teaching/learning sciences in non-formal contexts, which indicates the need to make bridges between the school curriculum and visits to museums (Falk, 1997).

The students' written answers to the questionnaires and reports were analysed qualitatively, taking as references answer categories that were shown in other previous research (Gil & Solbes, 1993; Ramada, Barve, Kumar, & Baba, 1996; Villani & Arruda, 1998), which were clarified and reformulated during the process (Ericsson & Simon, 1984; Kvale, 1996). Common tendencies have been identified in the students' answers, and representative examples of their answers have been included here.

This study has built on Jiménez-Alexandre et al.'s interpretation of Toulmin's Arguments Pattern (Toulmin, 1958) using a framework (Jiménez-Alexandre & Pereiro-Munaz, 2002, 2005; Jiménez-Alexandre, Bugallo, & Duschl, 2000) to analyze argumentation that occurs as students engage in decision-making activities in pre-visit and post-visit sessions. The analysis will help to determine how the students use evidence to support explanations and the quality of their argumentation.

Students' Knowledge of the Special Theory of Relativity and its Applications

One of the research questions within this paper aims to identify students' knowledge of and attitudes towards the STR. In this section we will present some of the students' conceptions. All of the conceptions presented are those shown by a minimum of 10 students.

In the case of the STR, the students found themselves in a new situation, which was not intuitive and not very predictable. The process of understanding this theory usually generates some anxiety, as they cannot usually draw on everyday experiences to accept its plausibility, or corroborate its efficiency (Alemañ, 1997; Pérez & Solbes, 2003; Toledo, Arriasseco, & Santos, 1997). In formal teaching, different studies highlight secondary school students' (14–18 years old) difficulties in acquiring an abstract vision of the concepts of space and time, which are differentiated from the explanations limited by perception and absolute reference frameworks (Castells & Pinto, 2001; Saltiel & Malgrane, 1980). Also, for first-year engineering students, analyzing the movement from a reference system outside oneself is some- thing that is only achieved with quite a lot of training (Galili & Kaplan, 1997).

The relationship between mass and energy is treated by students as a mere relationship between magnitudes, ignoring its equivalency, or without establishing a relation between them. Students are not usually capable of reasoning appropriately on energy in nuclear fission processes. Also, students do not usually know about the applications of STR and they consistently indicate that this knowledge has scarce value for them and for science.

In this paper, the most common trends in students' knowledge of STR and its applications are presented in Table 1.

The vast majority of the students confessed their ignorance of STR and they confirmed it when they were asked about the meaning of the equation $E = mc^2$ (Item 4 on the questionnaire). In this item they are asked to explain the following statement: 'Einstein states that when the total force on a body increases, the acceleration of this body does not always increase'. The majority of the students' reason,

Table 1. Students' knowledge detected in the pre-visit questionnaire

Conception (number of reports = 35)	Example answer
1. The theory is considered to be unrelated to everyday experience ($n = 10$) and they confess that they do not know the theory, or they do not answer ($n = 17$)	1. 'I don't know what the theory is specifically about, a lot of people talk about it, but nobody says what it is exactly. I think that it is applied in questions relating to space trips …'
2. Only 15 (43%) students mention between 1 and 3 applications of the theory (10 space exploration, 7 nuclear energy, 2 lasers and 2 atomic bombs)	2. 'It is applied to obtain nuclear energy; either in the form of an atomic bomb, or as a source of energy. In the study of space, black holes, etc.'
3. Notion that communications could one day be instantaneous (there is no limit for the speed of communications) ($n = 23$)	3. 'Communications will one day become instantaneous; they are not right now because of technical problems which will be overcome in the future'
4. Confusion between reference systems and bodies in movement ($n = 20$), when they have to explain that the same phenomenon can last for different times	4. '… if two clocks located in reference systems which move at different speeds mark different times, this is due to the fact that speed depends on space and time. Depending on the speed the body is moving, the body will take different amounts of time …'
5. When they are asked to explain the meaning of the equation $E = mc^2$ in words, 65% ($n = 23$) make superficial descriptions of the formula and only 5 students give a physical meaning	5. '… Kinetic energy is equal to the mass of the body, multiplied by the speed it is moving at squared'

in accordance with Newton's Second Law from classical physics, that Einstein's statement does not make any sense to them.

This same ignorance is reflected when enquiring into their knowledge of its applications. Only a minority of students could indicate an application. This result is consistent with the vision they have of STR, as something which is not related to everyday life (Pérez, 2003).

The majority of students had never wondered about a limit for the speed of light, or electromagnetic waves. This result is consistent with studies that indicate the teaching of optics and kinematics does not cover problems related to measuring the speed of light and its epistemological relevance (Villani & Arruda, 1998).

They do not know how to distinguish between a reference system and a moving body, and consequently they do not understand what it means to measure time in reference systems that move at different speeds. This result coincides with several studies that indicate student difficulties in understanding the meaning of Inertial Reference Systems within the framework of classical physics (Galili & Kaplan, 1997; Saltiel & Malgrane, 1980).

The concept of energy is one of the most fruitful and unifying concepts in physics, and is commonly used in technology, culture, and society. Maybe this explains why the most famous equation in science is $E = mc^2$. However, energy is also one of the most complex concepts in terms of learning and teaching difficulties (Doménech et al., 2007). These difficulties are reflected in the answers obtained in the pre-visit questionnaire, where most of them cannot provide any meaning for Einstein's equation. This result agrees with that obtained in the study by Solbes and Tarín (2004), which showed that the mass–energy equivalence, as it appears in the STR, is not understood by students in the final year of Spanish secondary education (18 years old), who cannot justify correctly the equivalence between mass and energy predicted in Einstein's equation.

The Exhibition's and the Teaching Materials' Potential to Influence Students' Knowledge

The second research question covers the exhibition's potential, in combination with the pre-visit and post-visit treatment in the classroom, to influence the students' understanding of STR.

Firstly, we are referring to the question of whether suitable design combined with the visit to a museum can increase understanding of the scientific principles. The majority of students explicitly indicate in their post-visit report that their knowledge of the STR and its applications has increased; for example:

> … the visit to the exhibition has helped me to understand why the speed of light in a vacuum is the maximum it can achieve. I didn't think that the Theory of Relativity covered this question. I was surprised by the simulation which justifies that the same clock can mark different times in different reference systems. Furthermore, I have seen interesting applications, such as the muons and radioactive elements …

From the students' comments it seems we can deduce that there is a subjective conviction that they have discovered new information and experiences which have helped them to understand some aspects of relativity better. The students express a better understanding of the STR's social use.

One interesting question was to find out whether some of the students' preconceptions, or distorted ideas, had modified as a result of the seminar and visit. Categorizing and analyzing the students' pre-visit questionnaires and comparing them with the post-visit reports show differences in some areas that were highlighted in the seminar visit.

It is difficult to evaluate adequately all of the answers given by the students. In order to characterize the responses, the comments recognized as 'an explanation' (Cortazzi, 1993) were coded for occurrence of some easily recognizable features, such as alternative conceptions, scientific statements, and argumentation from a scientific point of view. For example, in the first question of questionnaire (see Appendix), if the student's explanation has one or more scientific statements, which include justification based on evidence, the answer was considered correct and was included in the 'correct' category shown by the grey columns (pre-visit) and black columns (post-visit) of Figure 1. When the answers have any alternative conceptions or the statements are not justified, they are not included in the 'correct' category.

warrant for this argument might be the explanation of what Michelson and Morley's experiment shows.

Further support can come from backings that lend authority to the warrant. For example, the equations from the exhibition appear in all the reports, with justifications based on the STR:

> Because when the speed is very high, similar to the speed of light, Einstein indicated that the Galilean transformation breaks down. In the case of the torch and the rocket, it does make sense that the speed of the torch is: $v_{luz} = c + v_{cohete}$, but in accordance with Einstein's equation, if we suppose that the speed of the rocket is 0.9c, we have:
>
> $V_{luz} = 0{,}9c + c / 1 + (0{,}9c^2/c^2) = 1{,}9c / 1{,}9c^2 = c$

However, around 30% of students affirm that it is not possible to instantaneously transmit information. They do not justify the limited speed of light. These students use the exhibition information, but their explanations do not contain the elements of argumentation. For example:

> … if the information has to cover great distances, it cannot be instantaneous as electro- magnetic waves (light) must take some time and have limited speed … (Group 3)

Regarding the second aspect (the same phenomenon can last different times depending on the reference system), when looking at measuring the different intervals of time for the same phenomenon according to the chosen reference system, around one-half of the reports use justifications following the lines of the theory; explaining the example on the average life of the muons and the number that reach the surface of the Earth, which was described in the 'Time' simulation in the exhibition:

> This difference in time measurement for bodies close to the speed of light allows us to explain why large quantities of muons are detected at the Earth's surface without having disintegrated on their journey. (Group 9)

The report states that the same phenomenon can last different times depending on the frame of reference, and the data they use to support this comes from the 'Time' simulation of the exhibition. The support for this argument is the explanation for why a lot of muons are detected on the Earth's surface.

In reference to the third aspect (mass and energy), the relationship between mass and energy expressed by Einstein's famous equation, there are three different types of correct explanations: using the CERN simulation in the exhibition (31%); qualitatively differentiating between mass at rest and mass at high speeds (31%); and qualitatively reasoning about the impossibility of obtaining greater acceleration when more force is applied (38%).

An example of the first type of explanation is the following:

> In the 'energy' simulation we saw, in the CERN laboratory, that when particles obtain great speeds the mass and energy are equivalent and produce new particles … (Group 11)

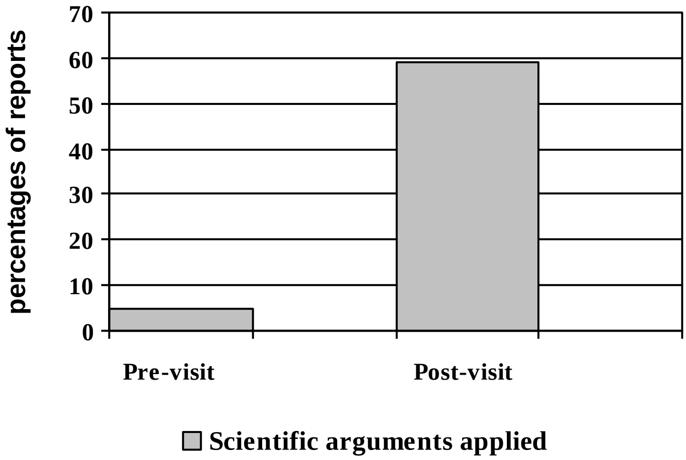

Figure 2. Use of scientific argumentation. Columns indicate the proportion of the students' reports in which at least two or three aspects considered in the exhibition are argued scientifically, before and after visiting the museums.

Although the students on the first-year engineering course have not received prior instruction on the STR, they have greater scientific knowledge than the average citizen. However, scientific argument was rarely used in the pre-visit questionnaire to support the statements they made. Also, in Spanish university classes, it is not usual for students to have the opportunity to argue and justify their ideas scientifically (Guisasola, Furió, Ceberio, & Zubimendi, 2003). However, in this piece of research it has been shown that, when the students are given information and appropriate questions to discuss, there is a significant increase in the use of scientific reasoning to defend their ideas.

Whilst student understanding clearly appears to have improved, the students do not always use the information they are given to develop the knowledge targeted by the exhibition designers. In the simulations and the panels that explained Einstein's famous equation, the students identify the equivalency between mass and energy:

> The formula $E = mc^2$ tells us that the mass and the energy are the same. (Group 6)

> The formula $E = mc^2$ permits us to obtain nuclear energy as the mass and energy are equal. (Group 7)

In other panels and simulations that recounted Einstein's thought experiment on clocks and measuring time in different reference systems, the students had to understand the counteraction or lengthening of the time in different reference systems. However, many students concluded:

> It seems that the clocks at rest and in the train measure different times for the same fact, but this is only one explanation; I don't think it really happened …

> Einstein's formula of time equivalence gives, as a result, different time measurements, but this is difficult to believe. I do not think that the time 'really' gets longer or shorter …

These answers correlate with other studies where it is shown that students do not reason effectively in terms of space–time properties; their minds requiring fixed properties (the distances measured are independent of the reference system; Villani & Pacca, 1987) and three-dimensional bodies, rather than points, for a realistic vision of nature (Gil & Solbes, 1993). The student admits that different observers 'seem' to obtain different measurements, but 'really' there is only one measurement of space, time, or the speed of light. Hewson (1982) showed how even the teachers themselves found it difficult to change this inaccurate concept of absolute space and time.

These erroneous answers, and other unexpected answers, show that inviting visitors to the exhibition, with the aim of getting them to integrate the information from the panels and simulations, and thus form their own opinion and conclusions, does not always have the desired effect. In this research, due to the chosen theoretical framework, it was clear that the students' preconceptions on relativity would influence their interpretation of the exhibition. Also, the last two examples show that students incorporate the new scientific knowledge along with other types of knowledge, on epistemological and moral values, to form an opinion on a scientific theory and its relationship with society. So, the students take on and use the scientific explanation that the clocks can mark different times in different reference systems:

'It seems that the clocks at rest and in the train measure different times for the same fact', and 'Einstein's formula of time equivalence gives different time measurements as a result and the "muon" simulation provided evidence for the theory'.

The students made the claim that clocks at rest and in movement measure different time for the same event and they provide data from 'the muon' simulation. Einstein's formula is used to backup the supporting argument. However, they do not incorporate the explanation into their system of beliefs: 'I do not think that it really happens' and 'I don't believe that the time "really" gets longer or shorter …'.

In order to investigate the effects of the seminar on students' attitude and interest to STR, we analyzed the last question of the sequence: What did you learn from the seminar? Many students gave more than one explanation, but the vast majority of students believed they were now (more) aware of the practical applications of the STR and they noticed that this theory was interesting for human development and everyday life. We scored the students' perception of the usefulness of the seminar and their interest in the STR, measuring the percentage of reports that included three or more applications of the STR; before and after the visit, respectively. The results are shown in Figure 3.

We also gathered information from informal talks to students after the visit to museum. Some students said that it was nice to have this type of seminar as a complement of their learning. They also asked for more of this type of activity, even in place of regular teaching.

Educational Implications

The results obtained have a number of practical implications for designing teaching sequences that use visits to science museums as a part of the teaching approach.

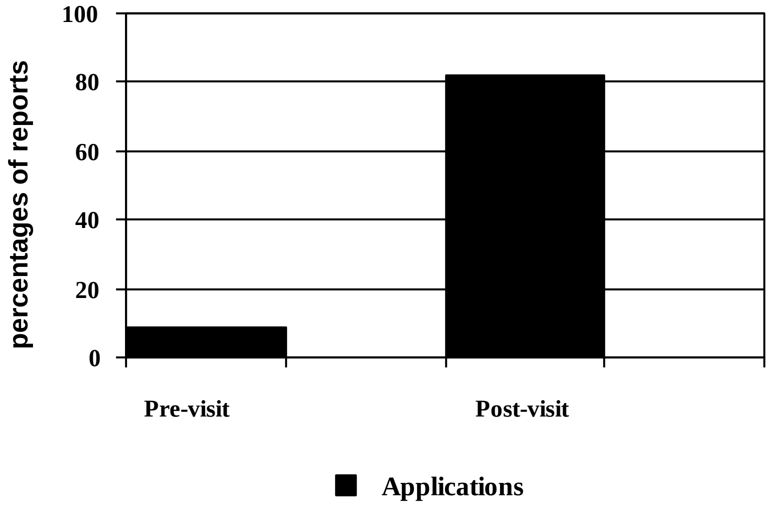

Figure 3. Students' perception of the usefulness of the seminar and their interest in the STR. Columns indicate the proportion of reports that mention three or more scientific–technical applications, with social implications, of the STR, before and after the visit, respectively.

A teaching sequence has been designed for this study in order to integrate the visit to an exhibition on the STR into what is happening in the classroom. In accordance with the theoretical framework proposed by Falk and Dierking (1992, 2000), the teaching sequence consists of three phases ('before', 'during', and 'after'). It should be noted that the pre-visit design, which includes activities and 'situations' that tie into the contents and objectives of the exhibition, requires a profound knowledge of the same on the part of the sequence designers. In the case we present, the designers of the teaching unit had participated in organizing the exhibition, which provided a natural take-off point for designing the different sequential phases.

Likewise, the school session activities have a dual objective; both informing the students of the content and objectives of the exhibition, and stimulating the students into scientifically arguing their explanations and to thinking about the problems related to scientific knowledge. This starting point has been shown to be useful when 'guiding' the search for information in the exhibition and analyzing the information.

Another important element in the organization of information in the teaching sequence has been the knowledge of the difficulties that students have in learning about the STR. Research into misunderstandings in physics has shown that these misunderstandings are similar in different countries and throughout the school age range. Museum education specialists, teachers, and designers of sequences of school visits to museums must find out visitors' possible misunderstandings in relation to the topics covered in their exhibitions, as these can interfere in the information transmission process and the process of building scientific knowledge, which they aim to achieve.

The results show that the teaching sequence and exhibition visit have increased the students' interest, knowledge, and understanding of the STR and its applications.

Likewise, after the plenary session the majority of students can adequately prove that the speed of light is constant and that it has a limit. However, meaningful learning of other aspects of the STR—such as that the same phenomenon can last different times depending on the reference system, or the qualitative relation between mass and energy at high speeds—has presented more difficulties and only a minority of students show a correct understanding. This may be due to the fact that a deeper knowledge of the concepts of the STR could require a sequence having more discussion, more sessions—and that would include a second visit to the exhibition.

It should be highlighted that only around one-half of the students involved in this study have shown the ability to argue and scientifically justify their ideas and their assessments of the STR. This could be due to the students not being used to arguing their ideas from a scientific standpoint and justifying their opinions within science classes. Providing students with experience, along with information, so that they can express their reasoned opinions on scientific theories and their corresponding applications, is one of the main components of scientific education. When school visit programmes are designed for museums, special care must be taken with the aspects that relate information on scientific concepts with scientific argumentation.

In this research, the teacher who took part in the experiment participated in designing and developing the exhibition, and so the designers of the teaching unit had a deep knowledge of the content and objectives of the exhibition. This is a great help in designing and implementing a teaching sequence to integrate a museum visit into classroom study. This will not usually be the case, but we think it is necessary for teachers or teams of teachers to be informed about the contents and objectives of the exhibitions prior to designing their teaching sequences. It is necessary to take into account the objectives of the exhibition and those of the curricula, in designing teaching sequences as a bridge between the exhibition and school-based learning.

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Appendix. Pre-visit questionnaire from the teaching unit

1. The possibilities provided by communication at increasing speeds are growing and we are already talking about a ‘global world’ and the enormous efficiency of new information technologies. Do you believe that it is possible that the time will come when communications occur instantaneously?
2. This year, World Physics Year is being held to coincide with the Centenary of Albert Einstein publishing the “Special Theory of Relativity” in 1905. What benefits has this theory brought to society? Give three practical applications.
3. One of the most famous statements of Albert Einstein’s Theory of Relativity is that two clocks situated in reference systems which move at different speeds mark different times. How would you explain this to your little brother or sister with an example?
4. According to the American magazine TIME, the most famous equation of the 20th century is: “$E= mc^2$” Could you explain in words, not formula, what this equation means? Give an example of the application of this equation.