Designing learning scenarios for a 3D virtual environment: The case of special relativity

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Abstract

Special Relativity, as introduced by Einstein, is regarded as one of the most important revolutions in the history of physics. Nevertheless, the observation of direct outcomes of this theory on mundane objects is impossible because they can only be witnessed when travelling at relative speeds approaching the light velocity c. These effects are so counterintuitive and contradicting with our daily understanding of space and time that physics students find it hard to learn special relativity beyond mathematical equations and to understand the deep implications of the theory. Although we cannot travel at the speed of light, Virtual Reality (VR) makes it possible to experiment the effects of relativity in a 3D immersive environment (a CAVE: Cave Automatic Virtual Environment). The use of the immersive environment is underpinned by the development of dedicated learning scenarios created through a dialectic between VR-related computational constraints and cognitive constraints that include students' difficulties. Investigating student's understanding of relativistic situations (that involve relative speeds close to c) led to the typifying of a cognitive profile that governed the situations to be implemented into the CAVE and the associated learning scenarios.

Keywords: Student's difficulties in special relativity, 3D immersive environment, event, reference frame.

Resumen

La relatividad especial, introducida por Einstein, es considerada como una de las revoluciones más importantes de la historia de la física. Sin embargo, la observación directa de las consecuencias de esta teoría en la vida cotidiana es imposible, ya que sólo puede ser visto cuando uno viaja a una velocidad cercana a la velocidad c de la luz. Estos efectos contradicen tanto nuestra comprensión cotidiana del espacio y del tiempo que los estudiantes de física tienen dificultades para aprender relatividad más allá de las ecuaciones matemáticas. De hecho, no logran en entender las profundas implicaciones de la teoría. A pesar de que no se puede viajar a la velocidad de la luz, la Realidad Virtual (VR) permite a experimentar los efectos de la relatividad especial en un ambiente inmersivo en 3D (una CAVE: Cueva Automática de Ambiente Virtual Medio). El uso del ambiente se basa en el desarrollo de escenarios de aprendizaje dedicados creados a través de una dialéctica entre las restricciones computacionales relacionadas con la RV y las restricciones cognitivas que incluyen las dificultades de los estudiantes. Investigar la comprensión de estudiantes enfrentados a situaciones relativistas (que implican velocidades cercanas a c) permitió resaltar un perfil cognitivo que orienta las situaciones que deben aplicarse en la cueva así como los escenarios de aprendizaje asociados.

Palabras clave: Dificultades de estudiantes en relatividad especial, ambiente de inmersión 3D, evento, sistema de referencia.

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I. INTRODUCTION

This research takes place within the context of the EVEILS research project (French acronym for Virtual Spaces for the Education and Illustration of Science). This project aims at exploring the innovating potential of Virtual Reality (VR) in several areas of science through an interdisciplinary approach involving physicists, VR specialists and physics education researchers. The project exploits advanced interfaces in order to confront a student with unusual phenomena otherwise inaccessible to human experience. The exploration of the cognitive modifications and pedagogical advantages associated with the 'immersion' is part of the main goals of EVEILS. This educational aspect makes EVEILS quite specific among the research programs devoted to computer simulations associated with VR [1].

Special Relativity, as introduced by Einstein, is regarded as one of the most important revolutions in the history of physics. Nevertheless, the observation of direct outcomes of this theory on mundane objects is impossible because they can only be witnessed when travelling at relative speeds approaching the light velocity c. These effects are so counterintuitive and contradicting with our daily understanding of space and time that physics students find it hard to learn relativity beyond mathematical equations and to understand the deep implications of the theory. Although macroscopic objects can not travel at the speed of light, Virtual Reality (VR) makes it possible to experiment the effects of relativity in a 3D immersive environment (a CAVE: Cave Automatic Virtual Environment)[1] where the speed of the light is simulated to a reduced value. The EVEILS project is a framework designed to merge advanced 3D graphics with Virtual Reality interfaces in order to create an appropriate environment to study and learn relativity as well as to develop some intuition of the relativistic effects and the quadri-dimensional reality of space-time.

II. OVERVIEW OF THE RESEARCH

The use of the immersive environment is underpinned by the development of dedicated learning scenarios created through a dialectic between VR-related computational constraints and cognitive constraints that include students' difficulties. Investigating students' understanding of relativistic situations (that involve speeds closed to c) led to the typifying of a cognitive profile that orientated the situations to be implemented into the CAVE and the associated learning scenarios (see Fig. 1). These scenarios aim at approaching the consequences of the invariance of the speed of light and more specifically the relativity of the simultaneity but also a deeper understanding of the concepts of "reference frame" and "event" (in physics). Here we will present the results of the characterization of the cognitive profile and its consequences on the development of the scenarios.

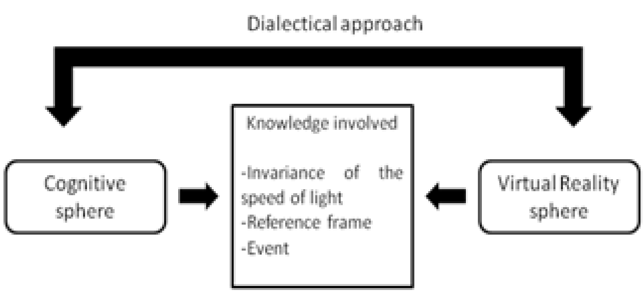

FIGURE 1. Diagram of the research process.

III. STUDENT'S DIFFICULTIES IN SPECIAL RELATIVITY: ELEMENTS OF THE STATE OF THE ART

The transition from classical to relativistic kinematics requires a radical change in the conceptual framework. In the theory of special relativity, c is a constant that connects space and time in the unified structure of space-time. The speed of light is equal to that constant and thus is invariant with respect to any inertial reference frame. Besides, the simultaneity of two events is not absolute (two events at different locations that occur at the same time in a given reference frame are not simultaneous in all other reference frames). Assuming this change in the conceptual framework requires a sound knowledge of the concepts of reference frame and event that underpin the laws of classical kinematics. A reference frame can be defined as a rigid body or as a set of observers at rest relative to each other. These observers determine the same distances and time delays between any set of events where an event is defined as a fact that occurs at a given location in space and at a given instant in time. A poor understanding of the concepts of reference frame and event can be a major obstacle to moving from the classical to the relativistic conceptual framework.

Studies conducted in order to characterize student's difficulties in special relativity are not very numerous. Nevertheless, from what have been explored we can detain that students fail in defining and using the concept of *event* [2] and thus confuse the instant of an *event* and the instant of the perception of that *event* by an observer [3, 4]. Moreover they use 'spontaneous' kinematics lines of reasoning (such as absolute motion, distances and velocities) to explain mechanical phenomena in both classical and special relativity frameworks [5, 6]. Students think that *simultaneity* is absolute and independent of relative motions [6, 3]. Students fail in understanding the concept of *reference frame* confusing "reference frame" and "point of view". Thus, each observer constitutes a distinct *reference frame* [3].

IV. EXPLORING STUDENT'S REASONING ABOUT *EVENT* AND *REFERENCE FRAME* IN THE FRAMEWORK OF SPECIAL RELATIVITY

Starting from the results obtained by Scherr's team we developed a test (see appendix) in order to address the following research questions:

- RQ1: How do students understand the concept of reference frame?
- RQ2: How do students understand the concept of event?
- RQ3: How is a classical kinematics line of reasoning involved in the resolving of questions where the relativistic framework is mandatory?

The research was conducted through the analysis of the students' responses to nine multiple choice questions

[1] A CAVE is a surround-screen, surround-sound, projection-based virtual reality system. The illusion of immersion is created by projecting 3D computer graphics into a cube composed of display screens that completely surround the viewer. It is coupled with head and hand tracking systems to produce the correct stereo perspective and to isolate the position and orientation of a 3D input device. The viewer explores the virtual world by moving around inside the cube and grabbing objects with a appropriate device.

including a request for justification. These nine questions involve two distinct situations. The first one, the "train situation", is implemented in the first question (Q1), the other eight questions (Q2.1 to Q2.8) form the second situation, the "situation of the bridge".

In question 1 (Q1), pulses of intense light are sent by a laser source located in a station platform. They are moving at the speed of light (*i.e.* 300 000km/s) within the platform frame in the same direction as a relativistic train running at the speed of 100 000km/s. Students are asked to determine the velocity of the photons emitted by the laser source according to an observer at rest in the train. The other questions (Q2.1 to Q2.8) rely on the following situation: it is night. Two tourists A and B stand motionless facing each other at each end of a bridge. C stands in the middle of the bridge and D stands motionless between A and C (he is equidistant from A and C). At a given moment C makes them sign to take a picture with flash. At the instant when they perceive C's signal (considering that the reaction times of A and B are identical), A and B emit a flashlight (Fig. 2).

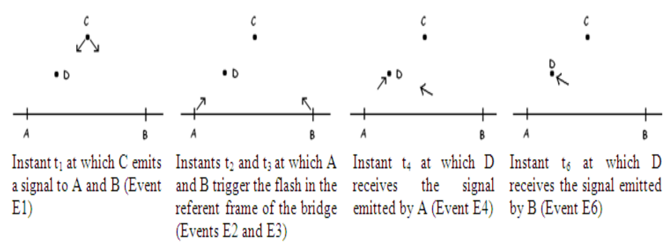

FIGURE 2. Chronological draws of the 'bridge situation' events.

Another tourist, E, is crossing the bridge on a relativistic scooter at a constant velocity (v=0.8c) relative to the ground. He is going from A to B and reaches abreast of C at the very moment he receives the light emitted by the two flashes. F follows E and crosses the bridge on a second relativistic scooter at the same velocity and in the same direction as E's. He is abreast of D at the very moment he receives the flash emitted by A. The questions are as follows:

- Q2.1. Does C perceive the light flashes at the same time?
- Q2.2. Have both flashes been emitted at the same time in the reference frame of C?
- Q2.3. Does D perceive the light flashes at the same time?
- Q2.4. Have both flashes been emitted at the same time in the reference frame of D?
- Q2.5. Does E perceive the light flashes at the same time?
- Q2.6. Have both flashes been emitted at the same time in the reference frame of E?
- Q2.7. Does F perceive the light flashes at the same time?
- Q2.8. Have both flashes been emitted at the same time in the reference frame of F?

TABLE I. Research questions connected with the associated concept involved in the corresponding question of the test.

Research question	Concept involved	Statement recovering the concept involved	Associated question
RQ1	Reference frame	For all observers (at rest relative to each other) of a given reference frame an event is defined by the same space-time coordinates (*i.e.*: if two events are simultaneous for one observer, they are simultaneous for all observers defining this reference frame).	Q2.2 Q2.4 Q2.6 Q2.8
RQ2	Event	When some observers have the same space-time coordinates as a given event, this event is identical for all observers.	Q2.1, Q2.5 Q2.3, Q2.7
		The emission of a light signal is a specific event different from the event corresponding to the reception of that signal as perceived by an observer.	Q2.1, Q2.2 Q2.3, Q2.4 Q2.5, Q2.6 Q2.7, Q2.8
RQ3	Relativistic kinematics	When a light signal is emitted by a light source moving with a constant speed with respect to a given observer, the velocity of the signal as measured by the observer is the same as the one measured in the reference frame of the moving light source.	Q1
		The simultaneity of two events in a given reference frame does not make sense in another inertial reference frame.	Q2.6 Q2.8

The questions are not all of special relativity. Only three of them (*e.g.* Q1, Q2.6 and Q2.8) require the implementation of relativistic reasoning. In addition, for each observer involved in the situation of the bridge, two different questions are posed: one concerns the instant of the reception of two signals, the other one concerns the emission of the signals. We explicitly distinguished the questions dealing with emission from these dealing with reception in order to access the cause that could lead the students to the simultaneity as relative: is the simultaneity relative to a specific reference frame (in accordance with the special relativity theory)? Is the simultaneity relative to a single observer (as it could be induced by a student confounding the order of emission and the order of perception)?

Moreover, students have information such as positions, speeds specific to a given reference frame. Consequently, they should be able to reconstruct the story of the light received and to trace "emission" event. The correct answers to the questionnaire involve the knowledge featuring in column 3 of Table I. We will infer from students' incorrect answers the ideas they have about each concept mentioned in column 2 of Table I.

The answer to RQ1 is provided by checking the consistency of answers to questions Q2.2 and Q2.4 and to questions Q2.6 and Q2.8. Indeed, A, B, C and D define the same reference frame, the reference frame of the bridge Rb (they are at rest relative to each other). Therefore, for these four observers, each event ("A triggers the flash" and "B triggers the flash") occurs at the same value of their common time coordinate. Similarly, E and F define the same reference frame, the reference frame of the scooter Rs (different from Rb). Thus, statements about the space-time coordinates of events should be identical for E and for F. Therefore we expect students to produce identical responses to questions Q2.2 and Q2.4 on the one hand, to questions Q2.6 and Q2.8 on the other hand.

To answer RQ2 we ask the students whether two events "A triggers the flash" and "B triggers the flash" are perceived at the same time by two different observers at rest relative to each other. The instant at which an event occurs is distinct from the instant at which the event is perceived by an observer. Consequently the location of the observer in a given reference frame induces a difference for the event "reception of a signal". For a pair of observers the instants of emission have unchanged values whereas the instants of reception are different since the duration of the light propagation is different. The time coordinate of events "emission of the flash" are the same for all observers at rest relative to each other whereas the time coordinate of events "reception of the flash" depend on the observer location. In order to see if students are aware of this aspect we have introduced a pair of observers in a first reference frame Rb (C and D) and a second pair of observers in a second reference frame Rs (E and F). We then examined the consistency of answers to the first four items and to the four following ones. We also examine the comprehension of the concept of 'event' with the following situation: two observers of two different reference frames are considered at the same space-time coordinates as that of the "reception of the flash". If students agree with the idea that two signals are received in the same order by both observers they should provide identical answers to Q2.1 and Q2.5 on the one hand, to Q2.3 and Q2.7 on the other hand. In response to RQ3 we try to see whether the students use the classical kinematics framework to investigate relativistic situations or not. Through Q1, Q2.6. and Q2.8. we seek to analyze the students' ability to identify the need to change the interpretive framework and to determine the extent to which students use the classical kinematics framework. These questions bring into play situations where the invariance of the speed of light and the relativity of simultaneity ought to be understood.

The research was conducted in France from May 2009 to January 2010. The study has involved 94 prospective physics and chemistry teachers (in France, physics teachers in lower and upper secondary schools have to graduate both in physics and chemistry and teach both subject matters) from five different teachers training institutes (IUFM). All are third-year graduate students in chemistry, or in physics or in physics and chemistry. The population includes at least 44 students who studied special relativity in their physics courses. The main part of the results of this study can be found in [8].

First we question the students about their understanding of a reference frame (RQ1). We examine the consistency of the answers to Q2 and Q4 on the one hand and to Q6 and Q8 on the other hand. 4% of the students surveyed give a justification resorting to observers pertaining to the same reference frame for the two sets of questions. And only 2% make a correct choice for the two sets of questions. In the light of this result it appears that students struggle in considering that in a single reference frame one event has the same space-time coordinates for all observers at rest in this reference frame. According to the students, two events may be simultaneous for one observer and not simultaneous for another one even if the two observers belong to the same reference frame. This is coupled with the fact that many students determine the instants of emission of A and B's signals by the instants at which these signals are received. This result echoes the results obtained by Scherr's team [3, 4]. This dependence between the instant of emission and the instant of perception seems to erase the difficulty associated with the relativity of simultaneity. The order of perception conditions the order of emission (despite an explicit consideration of the distance between the events and the observer), as if causality would apply from future to past, when it should be the opposite. Thus, if one does not distinguish between emission and perception then the issue of the non-simultaneity is not a problem but the concepts involved in special relativity are totally ignored.

Concerning the concept of event (RQ2), we examine the consistency of students' answer to Q2.1 and Q2.5 on the one hand and to Q2.3 and Q2.7 on the other hand. Only 13% (12 students) of the students answer Q2.1 and Q2.5 in a consistent way on the one hand and Q2.3 and Q2.7 on the other hand. It appears that most of the students surveyed cannot give an answer only depending on the space-time coordinate of the observer when his velocity is mentioned, as if the movement contaminated the event.

In order to answer RQ3 we ask ourselves whether the students use the classical kinematics framework to explain relativistic situations. We use two criteria: first, we wonder whether the property of an additive composition of velocities remains operational in a relativistic context (answer to Q1); next, we attempt to determine to what extent the simultaneity of events is seen as absolute (answers to Q2.6 and Q2.8). 28% of the students surveyed answer that the velocity of the photons is 200 000km/s (7%

at least had followed a course on special relativity). This result reveals a difficulty to accept that a velocity can be an invariant. Students know the numerical value of c as a invariant magnitude but do not all link this knowledge to the invariance of c consecutive to a change of reference frame. According to the second criteria, 33% out of the students who answer the Q2.6 and Q2.8 questions (whatever their choice of response) use a classical kinematics reasoning (with or without justification). This percentage is far higher than that of correct answers (12%) of which only two are properly justified in Q2.6 and Q2.8. We can notice that out of the students who chose the correct answer, six had attended a course on special relativity, and two of them gave a correct justification. This perspective suggests that the framework of classical kinematics remains dominant even after special relativity courses.

V. CONSEQUENCES FOR THE LEARNING SCENARIOS

Considering both VR-related computational and cognitive constraints we designed learning scenarios to be implemented into the CAVE. These scenarios aim at giving direct access to:

- The speed of light c is finite (and invariant), so we do not see the objects where they are now, but where they were when they emitted the photons that we perceive now. The determination of what a given observer effectively sees at a given location at a given time (*i.e.* at a given point in space-time), requires a framework in which the whole history containing the past positions of the various objects of the scene is accessible to find the emission event.
- Lengths and durations are not invariant and depend on the relative velocity between the objects and the reference frames involved. Thus, there is a priori a conflict between the intrinsic definition of the objects in their own reference frame and their actual occurrence in other reference frames, with respect to which they are moving. More precisely, Special Relativity teaches us that, in these other reference frames, the (instantaneous) lengths between two given points of the object are generally not the same. For instance, a billiard ball that is intrinsically a sphere, is no longer a sphere when described in the rest frame of the billiard board (see Fig. 3), with respect to which it is moving. This calls for a consistent description of the objects in any reference frame, *i.e.* in the 4D space-time reality itself.

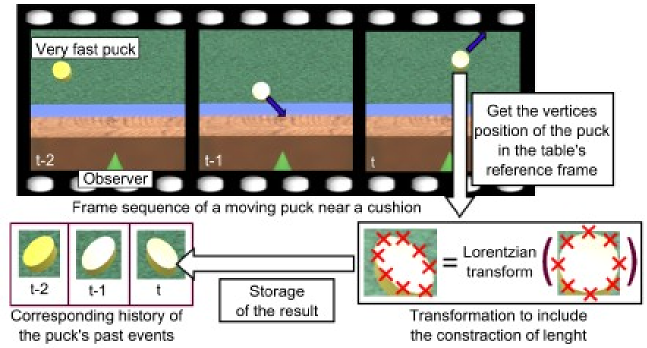

FIGURE 3. The rendering of a relativistic scene involves a search in the history of each vertex of the billiard balls. Each time an image is generated for the user, we store the position of each vertex at the current simulation time, after applying Lorentz contraction to the intrinsic definition of the objects. The history table built in this way can then be deep-searched through by dichotomy to find the emission event associated with each vertex, at any later observation event [9, 10].

The general idea of the scenarios is to confront users immersed into the CAVE with objects (billiard balls) moving on a billiard table (without frictions) at a speed approaching that of the light (Fig. 4). Interaction with the simulation is made possible by applying impulsions to the balls, to observe the limit velocity of light effect and the Lorentzian contraction of length in the carom billiard[2].

FIGURE 4. The carom billiard running in the EVE CAVE (CNRS/LIMSI, Orsay, France).

Furthermore, our application allows observing some subtle consequences of the theory of Special Relativity which are particularly important for physics education:

- The changes in the ball shape.

[2] To avoid overloading the simulation and affecting the understanding of the scene by superimposing effects of very different nature, we have not implemented the Doppler effect nor the effects of changes in light intensity. Indeed, we initially limited the rendering to purely geometrical effects (space-time and related concepts). The Doppler effect is certainly an effect of space-time, but its manifestation depends on the physical nature of light (electromagnetic wave which actually has a frequency...). In our approach, for now, we do not question the luminous phenomenon itself but the space-time architecture of the physical reality.

- The apparent acceleration and deceleration of the balls.
- The aberration of the light.

More precisely according to our first scenarios, users (who also are observers) are asked about changes in the shape of the balls and about the changes in their velocity. We also can question them about the instant of the contact of the balls with the billiard table. The proper time of each ball is visible. It represents the time measured by a clock located in the ball itself. The delay of reception of the photons by the observer (who is actually not located where the time is measured) is taken into account. Thus, according to the movement of the ball, the perceived time seems to pass faster or slower. Moreover, the movement of the ball can be "freeze" so that the ball is seen using the "Matrix" effect: a camera turns around the ball showing each part of it without changing the initial point of view which is the observer's one. The same scene can be replayed but as seen by an observer shifted on the left (or on the right). Then, two balls (of two different colors) are in movement perpendicularly to the billiard table. The observer can be located at equal distances between the red ball and the orange one. He can also moves to the left (or to the right) breaking the symmetry of the distances. All the effects observed are discussed.

We believe that using our application to experience these effects "without thinking" will help to develop intuition on relativistic behaviors while trying to play billiard properly at relativistic velocities. It is expected to help students in their efforts to understand Einstein's theory from a practical point of view. This will be tested by the EVEILS group through a dedicated research work in formal evaluations on physics students.

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Q1.

Pulses of intense light are sent by a laser source located at a station platform. They are moving at the speed of light (*i.e.* 300 000km/s) in the platform frame in the same direction as a relativistic train running at the speed of 100 000km/s. What is the velocity of the photons emitted by the laser source according to an observer at rest in the train?

a) 300 000km/s
b) 200 000km/s
c) We cannot answer
d) Other answer
e) I do not know

Q2.

Q2.1. It is night. Two tourists Alice and Bernard stand motionless facing each other at each end of the same bridge. Their daughter Cecile stands in the middle of the bridge. At a given moment, she makes them sign to take a picture with flash (considering that the reaction times of Alice and Bernard are identical). Does Cecile see the light flashes at the same time?

a) Yes, she sees the light flashes at the same time
b) No, she sees the flash of Alice first
c) No, she sees the flash of Bernard first
d) I do not know

Q2.2. Have the light flashes of Alice and Bernard been emitted at the same time in the reference frame of Cecile?

a) Yes, both flashes have been emitted at the same time
b) No, the flash of Alice has been emitted first
c) No, the flash of Bernard has been emitted first
d) I do not know

Q2.3. Denis is standing motionless on the bridge between Alice and Cecile. Does Denis perceive the light flashes at the same time?
a) Yes, he perceives the light flashes at the same time
b) No, he perceives the flash of Alice first
c) No, he perceives the flash of Bernard first
d) I do not know

Q2.4. Have the light flashes of Alice and Bernard been emitted at the same time in the reference frame of Denis?
a) Yes, both flashes have been emitted at the same time
b) No, the flash of Alice has been emitted first
c) No, the flash of Bernard has been emitted first
d) I do not know

Q2.5. Etienne is crossing the bridge on a relativistic scooter at a constant velocity (v=0.8c) relative to the ground. He is going from Alice to Bernard and reaches abreast of Cecile at the very moment she receives the light emitted by the two flashes. Does Etienne perceive the light flashes at the same time?
a) Yes, he perceives the light flashes at the same time
b) No, he perceives the flash of Alice first
c) No, he perceives the flash of Bernard first
d) I do not know

Q2.6. Have the light flashes of Alice and Bernard been emitted at the same time in the reference frame of Etienne?
a) Yes, both flashes have been emitted at the same time
b) No, the flash of Alice has been emitted first
c) No, the flash of Bernard has been emitted first
d) I do not know

Q2.7. Fanny is crossing the bridge on a second relativistic scooter at the same velocity and in the same direction as Etienne's. She reaches abreast of Denis at the very moment he receives the light emitted by Alice. Does Fanny perceive the light flashes at the same time?
a) Yes, she perceives the light flashes at the same time
b) No, she perceives the flash of Alice first
c) No, she perceives the flash of Bernard first
d) I do not know

Q2.8. Have both light flashes been emitted at the same time in the reference frame of Fanny?
a) Yes, both flashes have been emitted at the same time
b) No, the flash of Alice has been emitted first
c) No, the flash of Bernard has been emitted first
d) I do not know.