Learning scenario for a 3D virtual environment: the case of Special Relativity

de Hosson Cécile, Kermen Isabelle, Maisch Clémént, *LDAR, Université Paris Diderot-Paris 7 (France)*
Parizot Etienne, *APC, Université Paris Diderot-Paris 7 (France)*
Doat Tony, Vézien Jean-Marc, *LIMSI CNRS/Orsay (France)*

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 speed of light 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.

1. . 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)[1]. 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 (Savage et al. 2007).

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 speed of light c. The theory of Special Relativity teaches us that space and time are neither absolute, that is, independent of the observer (or the reference frame associated with the observer), nor independent from one another. Instead, they make up a global geometric structure with 4 dimensions, called space-time, whose "time" and "space" components depend on the reference frame used to describe physical bodies and events in terms of positions and instants. In particular, the length of a given object, as well as the duration of a phenomenon (between two well-defined events) will be – not only appear – different for two observers moving with respect to one another. 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, see fig.1)[2] where the speed of the light is simulated to a reduced value. The EVEILS project is a

[1] EVEIL is supported by the French National Research Agency (ANR) and conducted under the responsibility of Pr E. Parizot (APC Université Paris Diderot-Paris 7).

[2] 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

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. Of course, very early, mathematics were used to predict what objects would look like in relativistic motions and this have been applied to VR computing. Nevertheless, the specificity of the EVEILS project is to make physics education research actively involved in both conception and evaluation of the scenarios to be implemented into the CAVE.

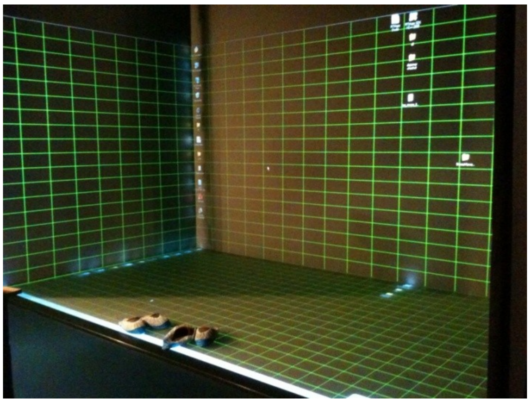

Fig.1: Picture of the CAVE used for the EVEILS project (LIMSI, CNRS/Orsay, France)

2. 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.2). 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.

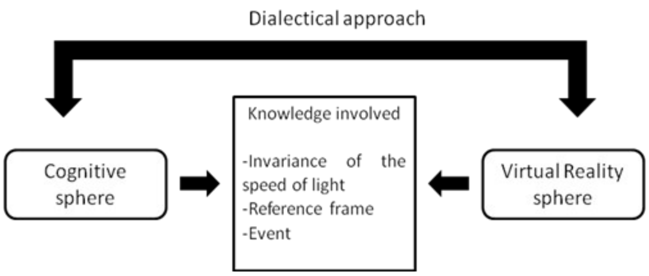

Fig.2: Diagram of the research process

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.

3. Students' 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.

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 use 'spontaneous' kinematics lines of reasoning (such as absolute motion, distances and velocities) to explain mechanical phenomena in both classical and special relativity frameworks (Saltiel & Malgrange 1980, Villani & Pacca 1987). Students think that *simultaneity* is absolute and independent of relative motions (Villani & Pacca 1987, Scherr 2001). Students fail in understanding the concept of *reference frame* confusing "reference frame" and "point of view". Thus, each observer constitutes a distinct *reference frame* (Scherr 2001). Moreover, they fail in defining and using the concept of *event* and thus confuse the instant of an *event* and the instant of the perception of that *event* by an observer (Scherr et al. 2001, de Hosson et al. 2010).

By connecting students with visual consequences of movements whose speed appears close to the speed of light we also hope we can reach a better understanding of concepts involved in the classical kinematics framework. This echoes various researches that pointed out the benefits of introducing modern physics in high school in order to improve fundamental concepts comprehension even in classical physics (Biseci & Michelini, 2008). This could also contribute to update the physics content taught in the secondary school context.

4. Confronting students to the 3D virtual environment

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:

- 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 puck that is intrinsically a sphere, is no longer a sphere when described in the rest frame of the billiard board (see figure III), 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.
- 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.

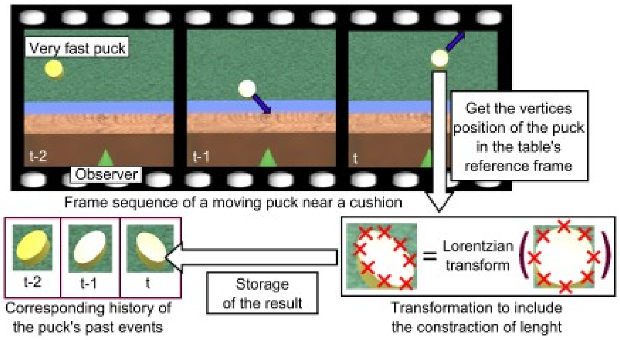

Fig.3: The rendering of a relativistic scene involves a search in the history of each vertex (point) of the billiard pucks. Each time an image is generated for the user, we store the position of each vertex at the current simulation time, after applying Lorentz contraction to the intrinsic definition 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 (Doat et al. 2011).

The general idea of the scenarios is to confront users immersed into the CAVE with objects (billiard pucks) moving on a billiard table (without frictions) at a speed approaching that of the light (figure 4). Interaction with the simulation is made possible by applying impulsions to the pucks, to observe the effect of the limited speed of light and the Lorentzian contraction of length in the carom billiard[3]. Indeed, our application allows observing some subtle consequences of the theory of Special Relativity which are particularly important for physics education:

- The changes in the puck shape
- The apparent non-simultaneity of the bounces
- The apparent acceleration and deceleration of the pucks
- The aberration of the light

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

With respect to students' spontaneous lines of reasoning (see above) we focused on the concept of *event* as defined by its coordinates in space and time in a given reference frame. Since the perception of an event (e.g. emission of light) by an observer depends on the time taken by the light to travel from the location of the event to the eyes of the observer, the signal travel time of light will impact the observations of the users immersed in the simulator. In everyday life the light signal travel time does not matter because it is close to zero whatever the location of the emission of the event. But when the students take it into

[3] 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.

account, they consider that the order in which two events occur is a consequence of the order in which these two events are perceived as if causality would apply from future to past (de Hosson et al., 2010). In our environment the signal travel time cannot be neglected (c is fixed to 1m/s), thus mundane objects are not seen as in everyday life. The simulator we designed takes into account the relativistic effects (simulation algorithms based on Lorentz transform, Doat et al., 2011) and also those due to the light propagation. Then we make the hypothesis that the users of our simulator will take into account the time delay between emission and perception in a relevant way.
According to our first scenarios, users (who also are observers) are asked about changes in the shape of the pucks and about the changes in their velocity. We also question them about the instant of the contact of the pucks with the billiard table. The corrected proper time of each puck is visible. It represents the time measured by a clock located in the puck 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 puck, the perceived time seems to pass faster or slower. Moreover, the movement of the puck can be "freeze" so that the puck is seen using the "Matrix" effect: a camera turns around the puck showing each part of it without changing the initial point of view which is the observer's one.

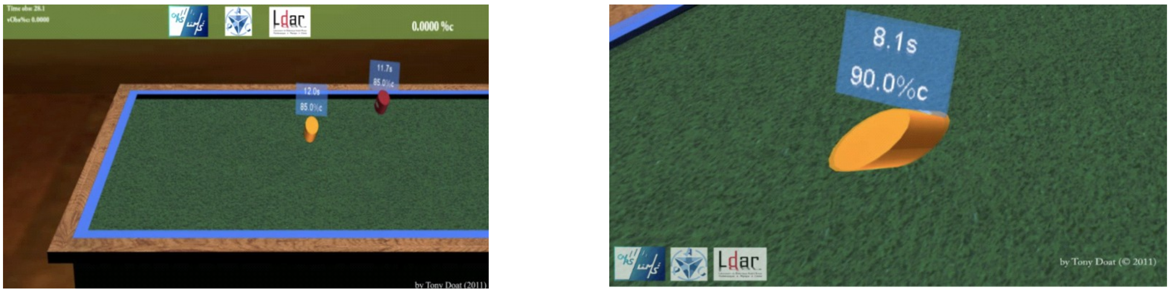

Fig.5: On the left screen-capture the apparent collision delay is observed; one the right screen-capture the observer can see the object deformation as an effect of the consideration of the finite value of c. The photons that arrive into the eye of the observer have not been emitted at the same time. The image seen is not the result of the emission of photons emitted simultaneously.

The same scene can be replayed but as seen by an observer shifted on the left (or on the right). Then, two pucks (of two different colors) are in movement perpendicularly to the billiard table (fig.5). The observer can be located at equal distances between the red puck 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.

5. Conclusion and perspectives

Five users were immersed in the simulator and had to explain what they saw when confronted to the learning pathway. We undertook a lexical analysis searching for some specific conceptual elements that we consider as key points for the users' understanding. These elements are the following: a) the incoming of light in the eye, b) the finite nature of the speed of light, c) the distance between the pucks and the user, d) the object discretization (a set of points as punctual sources of photons), e) the geometrical relativistic effects explained by the Lorentz transform. Following users' reactions during the immersion, we detected which situations favour the emergence of the conceptual elements that allow a relevant interpretation of the situation. As a conclusion the immersion of users in the 3D environment where they are confronted to relativistic phenomena favours lines of reasoning that take into account the light travel time and the arrival of light into the users' eyes.

We believe that using our application to experience these effects "without thinking" will help to develop intuition on relativistic behaviours 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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