Teaching Special Relativity using Virtual Reality

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Introduction

Learning Special Relativity is a highly anticipated experience for first year students; however, the teaching and learning of Special Relativity are difficult tasks. Special Relativity, while fundamentally and mathematically simple; has apparently bizarre implications and deals predominately with situations outside everyday experience. Understanding relativity requires one to accept that there is less that is absolute than was once believed and to accept a model of time and space that is strange and unfamiliar (Mermin 2005). As such, modifying everyday concepts of motion, time and space to develop accurate constructs of the theory of Special Relativity is extraordinarily difficult (Scherr, Shaffer and Vokos 2001; 2002; Scherr 2007). While Special Relativity is often featured in introductory physics courses, Scherr (2001) indicates many students fail to develop fundamental concepts in Special Relativity even after advanced instruction. To address these issues there has broad variety of efforts to determine the conceptual misunderstandings and develop activities to address them (Belloni, Christian and Dancy 2004; Carr, Bossomaier and Lodge 2007; Gamow 1965; Mermin 2005; Scherr 2007; Taylor 1989).

Real Time Relativity (*RTR*) is a virtual reality simulation of Special Relativity. Giving learners real time control of how they explore and test the optical, spatial and time effects of near-light-speed motion in a realistic environment enables a constructivist approach, previously unavailable, for learning Special Relativity.

Given the hands-on nature of *RTR*, it has been incorporated into the experimental laboratories of first year physics courses at the University of Queensland (UQ) and the Australian National University (ANU). These experiments enable students to explore relativistic effects without requiring a detailed understanding of the theoretical framework. *RTR* experiments have been developed with an active learning approach (Hake 1999; McDemott and Redish 1998) in which students learn by developing, testing and refining their constructs with their peers. The *RTR* system and experiments are currently being refined in a model inspired by the Physics Education Technology group at the University of Colorado (Adams, Reid, LeMaster, McKagan, Perkins and Wieman 2008) and evaluated through a multimethods research approach (Schutz, Chambless and DeCuir 2004). This paper outlines our current point in a continuing development and evaluation project.

Real Time Relativity

RTR simulates the visual effects of the finite speed of light and Special Relativity when travelling at near light speed. *RTR* is a game-like experience where the user controls his/her speed, direction of motion and direction of view around a world built of clocks, planets and abstract shapes. Within *RTR*, the Doppler and headlight effects can be toggled to avoid obscuring other effects and the speed of light may be set as infinite to allow the user to become accustomed to navigation controls and the virtual world. Otherwise the user is immersed in an authentic virtual reality where they can experience and experiment with visual, space and time effects while travelling at near light speed.

Savage (2007) describes the relativistic optics implemented in *RTR*, the hardware utilised and recent hardware advances that have made this visualisation possible in real time. He also provides an overview of the software algorithms utilised to create development versions of *RTR*.

The version 1.0 of *RTR* features a complete redevelopment for stability, efficiency and sustainable further development. *RTR* 1.0 utilises the OGRE 3D engine for cross platform support and greater ease of graphical implementation. The user interface rebuild provides a more user friendly system for users and teachers, also eliminating some common misconceptions, thus improving support for students developing accurate models for Special Relativity. Multiple user input control options have also been introduced. These changes seek to further improve the level of student engagement and interest in *RTR*.

Learning Special Relativity

The concepts of reference frames, time dilation, length contraction and the relativity of simultaneity are repeatedly highlighted as core concepts for understanding Special Relativity (Mermin 2005; Scherr, Shaffer and Vokos 2001; 2002; Taylor 1989). Mermin (2005) also recognises the importance of quickly conveying to students just how strange the effects of movement at high speeds are, which is an essential step before students can accept and internalise the concepts of Special Relativity.

For an introduction to Special Relativity, *RTR* provides an immediate visual experience of how different the world is when travelling at near light speeds. Figure 1 shows the spaceship users control in RTR both stationary and moving at near-light-speed through a world. When stationary the spaceship can be observed above a striped landscape facing along the direction of two clocks. When in the same position but travelling at a near-light-speed of 0.97c aberration, length contraction and distortion produces a scene where; previously straight lines curve and are thinned, a cube that is behind the ship appears to the left, the stars become concentrated and the clocks shrink and move to the middle of the field of view.

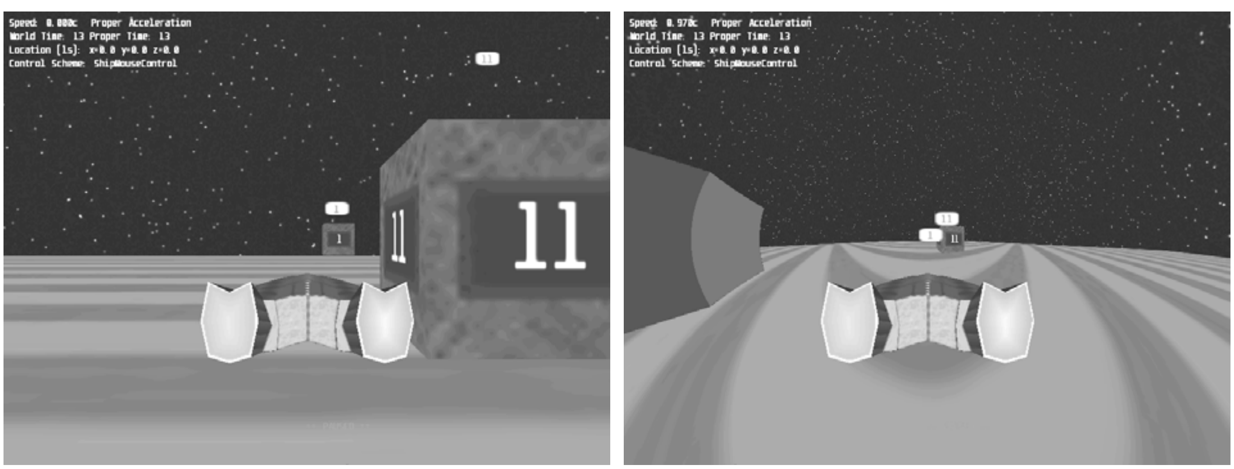

Figure1. Screenshot from *RTR* showing 2 clocks from the same location and angle when stationary (left) and when travelling at near-light-speed (right). Headlight and Doppler effects are turned off here.

In *RTR*, there are two reference frames; the reference frame of the ship and that of the static world. Students can change the reference frame of the ship by 'accelerating' or 'decelerating'; enabling students to develop and test models of reference frames. Length contraction can be directly observed by examining the change in the perceived length of objects in the world as the ship moves through different reference frames. Clocks in the world provide an opportunity to test time dilation and light delay. Multiple clocks are synchronised in the reference frame of the world but not in the relatively moving reference frame of the ship. Students experience relativistic optics observing aberration, and optionally the Doppler Effect and the headlight effect.

Special Relativity experiments

The challenge for the laboratory situation is how to provide suitable preparation and guidance to enable learners to actively experiment with *RTR* and negotiate their models for the observable effects, which is recognised as crucial for the success of a simulation in promoting learning (Adams, et al. 2008; Mazur 1997; Yeo 2004).

The laboratory sessions are run throughout the semester both before and after the lecture and tutorial series on Special Relativity. Students at ANU prepared for their Special Relativity experiment using videos and readings on Special Relativity, and on the effects of near-light-speed motion, from the 'Through Einstein's Eyes' web site (http://www.anu.edu.au/Physics/Savage/TEE/), and then completed a series of questions. At UQ, students were required to read a section of their textbook and complete a series of questions. The UQ experiment utilised a java applet to examine the pole-in-barn paradox, working with animations showing movement through one space dimension and time with matching Minkowski space-time diagrams before students explored *RTR*.

In both universities, students worked in small groups with tutor support for up to three hours. Their first activity was exploration of the world to develop competency with the user interface and an awareness of the virtual environment. Students were then guided through a variety of activities to observe and validate the Doppler Effect, light delay, time dilation, length contraction and (at ANU only) the relativity of simultaneity. Students were encouraged to question the accuracy of their measurements and seek sources of errors in how they managed their experiments. Diminishing levels of scaffolding were provided to initially engage and support students interpreting the world of *RTR*, while challenging students to make significant cognitive steps to complete their experiments.

Evaluation

The *RTR* software and experiments are being evaluated through a combination of surveys, observation, focus groups, interviews, trials and peer review. During semester students completed surveys before and after performing their experiments. UQ students were observed performing their experiments, and selections of them were informally interviewed to elaborate on responses and explain observed behaviours. Informal interviews of laboratory tutors were also conducted.

In preparation for Semester II experiments, focus groups of Semester I students at UQ were conducted and new activities and features will be evaluated through peer review and with student test groups. Throughout the semester pre-tests and post-tests will be implemented to supplement the surveys and observations at both institutions.

The pre-experiment survey was constructed to examine students' views on physics, laboratory experiments, Special Relativity and computing. A post-experiment survey explores students' views of their learning, concepts and experience of *RTR* and its use in comparison with other laboratory experiences. The surveys were developed from survey tools exploring students' attitudes to maths, physics and laboratory activities (Adams et al. 2006; Cretchley and Harman 2001; Read and Kable 2007). The survey was analysed for validity through student focus groups and checked for internal consistency.

Observation of student activities was conducted by an author (DM) who was otherwise not involved in the physics course, noting evidence of substantive conversations, times for activities and recurring issues and questions.

Results

Students find Special Relativity is more abstract than other areas of physics. (70% agree or strongly agree), after using *RTR* 72% of students would like to learn more about Special Relativity, 78% would like to use more simulations in their studies and 90% claim they enjoyed the experience, and only 2% of students surveyed claim to not have enjoyed the experience. Students generally reported enjoying trying new things on a computer (86% agree or strongly agree), finding simulations to be an effective way to learn (79% agree or strongly agree), and feeling comfortable playing 3D computer games or using 3D simulations (80% agree or strongly agree). We found no significant correlation between any factors on the pre-survey and the post-survey (N = 45).

In responding to open questions, students perceived the main lesson of this experiment as a subset of the effects investigated e.g. 'Length contraction, distortion of objects' (48%), the whole of 'Special Relativity' (31%) or a recognition of the significant difference of travel at near light speed (21%): 'Special relativity is crazy but cool'. When asked what they enjoyed, students highlighted the *RTR* simulation (31%), visual effects or the visual nature of the experiment (52%) or the conceptual focus of the experiment (14%). For example one student most enjoyed "thinking about why the effect occurred".

At UQ an introductory open activity in *RTR* provided unexpected difficulties for students. Students were required to make observations of the visual changes between being stationary and moving at near light speed with reference to the world of *RTR*. Students were overwhelmed by the compounding effects and could not match specific observations to their constructs of Special Relativity. 80% of the student groups who were formally observed (N=20) required tutor assistance to confirm and identify visual observations.

Observation showed every student group spent time engaged in substantive conversation as described by Newmann and Wehlage (1993) about the theories and representations of Special Relativity. For example when students verified the Time Dilation formula, they were confronted with a pair of clocks with a time difference that changed depending on the location of the observer. In this situation students negotiated ideas and tested theories using *RTR*, utilising their ability to observe clocks from various locations in time and space. Some student groups required laboratory tutor guidance, and significant time and effort: however this process resulted in all students eventually developing working concepts of the effects of light delay that they then applied to verifying Time Dilation.

A combination of observation and survey data showed that age, gender, prior computing, virtual reality and 3D gaming experience had no significant impact on students' experiences in the laboratory.

The separation of laboratory from lecture and tutorial content did not have a significant effect on student outcome and activity as evidenced by no significant change after the relativity lecture series in either survey responses or observed behaviour. This supports the continuation of a separated laboratory and lecture series as recognised by Toothacker (1983), allowing more efficient use of laboratory resources.

Students using early versions of *RTR* reported user input as the main area for improvement for *RTR*. UQ students reported the interface as an area for improvement but that it did not hinder their learning or activities. Students took on average twenty-three minutes (with a range of fifteen to thirty-three minutes) to complete an initial familiarisation activity where they became aware of the interface, environment and basic effects of *RTR* which was considered suitable within a three hour laboratory session.

Students had difficulties identifying the scale of the *RTR* environment, which was confounded by the reuse of an Earth object. One Earth was scaled appropriately but then so small as to be hard to notice. A second Earth was significantly larger and included as a familiar object to observe distorting effects. This loss of scale hindered students' recognition of light delay.

A significant proportion of questions asked by UQ students in the laboratory were a result of students not reading instructions. For example students often requested tutor support rather than reading documentation to find software functions. Pre-reading was not effective for a number of students to develop the desired background knowledge of concepts including the finite speed of light, light delay, length contraction or time dilation. These students required extra tutor support to fully engage in their laboratory experiments.

At UQ the individual tutor guiding a group of students had a significant effect on the experience and focus of a student group. For one activity the times recorded with one tutor's groups were on average double that of those recorded in another tutor's groups. While there was no significant change in the overall time taken for the experiment, this change in student experience may affect both how and what students learn.

Conclusions

The students who have undertaken experiments with *RTR*, have reported benefits both in understanding and heightened enjoyment from these activities. Students have demonstrated enthusiasm for the software, laboratory experience and subject matter without bias on the basis of age, gender or computing experience.

In evaluating students' experiences against the seven principles described by Chickering and Gamson (1987), the experiments implementing *RTR* have been observed to add significantly to learning of Special Relativity through; encouraging co-operation among students, promoting active learning, giving prompt feedback, providing more concrete representation, and facilitating visual and kinaesthetic styles of learning.

In redevelopment and refinement of these experiments, we are making the experiment more focused on conceptual development and further reducing the requirements for quantitative verification of formulas. The revised experiments will work from guided to open activities, to support students' development of understanding of the overlapping effects while gaining the benefits of the open experimentation *RTR* facilitates. Laboratory manuals for students will examine the scale of *RTR* both explicitly through images and descriptions and implicitly with references to the force one would experience when accelerating in *RTR*. We will further experiment with the objects and their organisation within *RTR* and their effects on students' concepts of scale. Along with these changes we are introducing more explicit documentation and training for laboratory tutors.

Evidence of the effects of Special Relativity coursework on *RTR* experiments has been collected; however we are yet to explore the effect of *RTR* experiments on students' experience of other coursework beyond the review of students' examination results showing no detrimental effects in traditional assessment of Special Relativity (Savage 2007).

Our research is now focusing on analysis of specific conceptual development and the transferability of our findings to other topics. Pre-test and post-test of students will provide an overview of the students' concept development when experimenting with *RTR*. Refinement and testing of new laboratory experiments, particularly with new functionality in *RTR* to modify and build environments, will enable us to build specific experiences, targeted to specific concept discovery and student cohorts.

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Real Time Relativity is available from: http://www.anu.edu.au/Physics/Savage/*RTR*/
The Teaching Physics Using Virtual Reality project site is: http://www.anu.edu.au/Physics/vrproject/welcome.html

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