Special Relativity in Immersive Learning

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Abstract. In this paper, we discuss our development, implementation and evaluation of an interactive, real-time, and real-scale virtual reality application used to understand the theory of special relativity. Since special relativity deals with non-trivial counter-intuitive subjects such as the twin paradox and the Lorentz contraction, we utilize an immersive VR experience to visualize these phenomena. In doing so, we attempt to teach the theory of special relativity in a manner different than conventional abstract methods. In this study, we tested a set of participants and examined their understanding of special relativity theory before and after engaging with the VR experience. Using the results, we inspected for any correlations between their perceived immersion during and after the simulation and their acquisition of special relativity theory.
Our study has shown that visualizing the phenomena of special relativity in VR led to high immersion among participants and increased knowledge about the theory of special relativity. With this work, we hope to build upon the collective knowledge about the effects of learning in a strong, visually pronounced, and highly immersive environment.

Keywords: Special Relativity · Virtual Reality · Immersive Learning · User Study

1 Introduction

Special Relativity [1] is one of the most prominent developments in modern physics. Its effects capture peoples interest, those of which are often described as counter-intuitive and contradictory to real life experiences of space and time. However, in teaching the subject, many students fail to develop an understanding of the fundamental concepts even after advanced instructions [2]. In part, misconceptions concerning Special Relativity Theory (SRT) stand as a barrier to mastering Einsteins mathematical formulations.

Our goal is to create an interactive and immersive simulation that improves users' skills with SRT [1] and resolve the challenges most people face with understanding the implications and intuition of Special Relativity [2].

Moreover, the use of our simulation extends beyond just the university level of education and into Secondary Education (S.E.) and anyone interested in SRT.

Early approaches like Gamows *Mr. Thompkins in Wonderland* [3] attempts to educate readers about relativistic situations using a vivid description of a relativistic world where the speed of light is reduced to 30 mph.

Nowadays, computer simulations in two and three dimensions aim to add intuitive understanding of SRT. Virtual Reality (VR) makes it possible to immerse the learner into a Virtual Learning Environment (VLE) [4] that is enhancing, motivating and stimulating learners' understanding of certain events [5] [6]. Our VLE scales velocities close to the speed of light revealing a relativistic world.

It has been shown that a carefully designed physics simulation can offer a level of comprehension that exceeds an understanding built during a traditional physics course [7]. Visual simulations can be highly engaging and educationally effective [7] , especially if they have been carefully designed and tested. According to W.K. Adams et al. [7] simulations should encourage exploration and provide a high level of interactivity while limiting elements of distraction. They should be designed to offer enjoyment and avoid appearing intimidating or boring. Students must believe in the VLE in order to engage with it. In addition, students who believe they lack an understanding of the ideas presented by the VLE are more likely to explore and learn from the experience. Essentially, it is easier for students to build an understanding of scientific concepts unfamiliar to them when they engage with visual stimulation.

Hence, we believe providing a VLE to explore special relativity phenomena can improve students' conceptual understanding of Einsteins Theory of Special Relativity, a theory that is among the most misunderstood topics in modern physics, the specifics of which include: relativity of simultaneity, length contraction, and time dilation [2, 9]. Our goal is for students to gain a complete conceptual understanding of the SRT, in particular time dilation (twin paradox) [10] and Lorentz contraction (aka length contraction) [11] [12], as they outline the phenomena. In addition, we will pose questions regarding the twin paradox to help reveal students intuitive understanding of special relativity.

Already existing computer programs such as *PhysLet* [13], *Spacetime*, *RealLab* [14] and many others [15–17] offer 2D visualization and try to demonstrate to a student special relativity phenomena otherwise inaccessible to the human experience. In addition to two dimensional simulations, some authors have investigated 3D simulated environments such as *CAVE* [18, 19] and *Real Time Relativity* [20, 21] as well as VR for teaching special relativity [22]. One study by McGrath et al. [21] using *Real Time Relativity* was conducted on over 300 students. Students report a positive learning experience and see the subject area as being less abstract after use of the simulation. However, no analysis on the improvement of the student's understanding has been done.

Research on the effectiveness of those simulations is either incomplete [21] [15] or just on a limited student population size [19] and assumes that the simulation will help to develop intuition on relativistic behaviors without any in-depth investigations [18], nor do any of them provide a large scale environment necessary to grasp the order of magnitude of SRT, such as including large stellar structures (galaxies) as well as smaller locations (solar system). This is of importance, since the Lorentz effect flattens the whole universe in flight direction, making it possible to traverse through the galaxy within seconds, depending on the speed. The dense stars of our galaxy, due to their numbers, are the major visual feedback to illustrate this effect.

The research presented in this paper focuses on investigating how VR experience can enhance students' knowledge and understanding of scientific topics. In particular, we look at how an individual's knowledge and application of SRT changes from before to after the use of a VR simulation and then gather data about each individual's level of immersion in order to conclude its effect on their learning [23]. Immersion with regards to VR is a cognitive state influenced by factors within and around a VLE. Immersion is composed of different psychological faculties such as attention, flow, engagement, planning and perception, and is qualified by a lack of awareness of time and the real world around an individual [24]. Additionally, it is the involvement and sense of existing in the simulated environment. Methods of measuring immersion have been investigated in subjective approaches [25], eye-tracking methodologies [26], non-interactive [8] and interactive media [23] using questionnaires [23], with latter one used in this work.

2 Methodology

We tested a group of n = 34 participants and conducted our research in four steps. Step 1 was to assess participants' demographics and existing skills in SRT using a pre-questionnaire. In Step 2, participants watched a lecture video about special relativity, developed by us. This video aimed to equip our participants with the most basic understanding of SRT to gain a fundamental level of abstraction. For step 3, participants engaged with the VLE experience. Finally, in step 4, participants answered post-questionnaire to assess their level of immersion and quantify any improvement in knowledge.

For this research, a real-time and real-scale simulation was developed to let the participants travel inside our solar system. The simulation included all 8 planets, and all moons bigger than 50 km in diameter, and allowed for user to navigate and explore the Milky Way with its diameter of 100,000 light-years (ly), in order to exhibit the large scale effects of SRT. In comparison to similar VLE's [13] [14] [15] [16] [17], the user will be immersed in a stereoscopic 3D environment by wearing a head mounted display (HMD), allowing free head movements.

The effect of Lorentz contraction happens only along the flight direction and is hardly visible from front view. To see the effect from the side, where it is most prominent, including Lorentz rotations [31], the flight direction and the view direction needs to be de-coupled, which is provided by the HMD. To achieve that in non-VR, 3D simulations must utilize two input methods, one for the flight direction and one for the view angle, which makes it over-complex to control, is in general not popular in games, and was consequently entirely left out in non VR approaches [18, 19, 21, 20].

Prior and post to the VLE, a mandatory questionnaire that assessed the user experience was conducted. We collected demographics in the first questionnaire prior to the VR simulation, as well as education related question about the state of special relativity skills.

We identified two long existing myths in SRT: The first, that moving clocks appear slower in general, which is not true. In the twin paradox, which has profound evidences [27], there must be phases of observing faster passing time for one twin, in order for the other one to end up older when meeting again. In fact, when approaching, both clocks would observe the others running faster, but whoever is changing direction would delay this effect, resulting in different aging [10]. The second myth is the general statement, that spheres do not change its shape under Lorentz contraction, but this is only true if seen from the front, it indeed flattens by the flight-direction dimension.

Furthermore, a survey was conducted to make a connection in how far immersion is related to the learning outcome. We used two different sets of questions to assess the immersion in different categories about what participants felt during and after the VR experience [28, 23].

We used two PC's equipped with an NVIDIA 1080Ti graphic cards each and Oculus Rift HMDs. Further on, OpenGL was chosen for the graphics programming and OpenVR to access the HMDs.

2.1 Pre-Educational Video

The video [29] we developed aims to provide a basic framework and elemental level of understanding of SRT and consequently levels out bigger educational gaps of the participants. This pre-educational video does not answer the questions raised in the questionnaire of this work. One must rather derive the answers from a deeper understanding gained from the VR experience. It's purpose is solely to provide an abstract framework. It starts by deriving the Lorentz factor γ [12] and the term 'relativity' as well as the constant speed of light is postulated. Further on, the individual time frame, depending on γ is explained, followed by an introduction to Minkowski diagrams. These diagrams are platform for introducing the concept of simultaneously events from the perspective of an observer and a moving spaceship, stating, that the spaceship system has its own axis of simultaneously events, but keeping in mind the aspect of relativity. The observer and the spaceship must be able to derive the same observation about each other as long as they are not leaving their inertial frame of reference.

2.2 Galaxy Simulation

Development Our VLE displays one million stars distributed across 100,000 ly (average disc diameter if the milky way) as well as all planets of our solar system, including the sun and all moons larger than 50 km in diameter. Due to the high density of stars close to the center of the milky way, we used it as landmark for one of our task, in order to have a better visual feedback illustrating the Lorentz contraction.

We developed the simulation in C++ and OpenGL, with a self written graphic engine specifically designed for displaying objects with massive size differences. As an example, our simulation's Earth rotated around the sun with $7,292115 * 10^{-5}$ rad/s which pushed the limits of 64 bit floating point precision. In another instance, when travelling on speeds close to the speed of light (c), the fraction $\frac{v^2}{c^2}$ of the Lorentz factor $\frac{1}{\sqrt{1-v^2/c^2}}$, in respect to the double-precision floating-point format, limits the speed at the eighth digit after the decimal and consequently does not allow to go closer to the speed of light. With a speed of $0.99999999c$, the spaceship would take several days to reach the center of the galaxy, which is not feasible for a user study. To overcome the double precision limitation, we used an arbitrary precision library [30] with 512 bit precision. Consequently, the maximum speed our simulation is $(1 - 10^{-24})c$. Arbitrary precision libraries however perform much worse than system-native floating point formats. Since our simulation runs in VR, every frame must be built in a timeframe $\frac{1}{90}$ of a second at maximum, in order to use the fix frame-rate requirement of the VR headset Oculus Rift of 90 frames per second (fps). To achieve the high frame-rate, we only utilize the arbitrary precision library to calculate the spaceship speed, position, as well as the positions of the planets and moons, based on their rotation.

As for the simulation itself, participants control a spaceship. The spaceship's cockpit consists of several panels, see Fig. 1. Starting in the upper-left corner is information to orient participants. The information includes the distance to a selected destination in light-years, the elapsed time relative to the spaceship, the elapsed time relative to Earth, and the current travel speed as a factor percentage of the speed of light. The spaceship's location is provided by a map displayed on the left. On the right side of the screen are autopilot controls which allow travel to any of the provided destinations. These destinations include all solar planets, the sun, and the galaxy's center and outer most bounds. Alternatively, participants can use the WASD keys on the keyboard to move around manually. The 'W' key accelerates the spaceship and 'S' stops it. The 'A' and 'D' keys rotate the screen left and right respectively. The flight direction is indicated by a red circle in the center of the screen, see Fig. 1. There is a pause button that can pause the simulation's time progression. At the bottom is the task window where participants can toggle through orientation instructions for the VLE and the three tasks we assigned them which we will elaborated on later.

The simulation always starts a participant's spaceship at Earth. Pressing the 'enter' key during the simulation will reset them back to this place. Pressing the space bar hides all screen and cockpit information as an attempt to decrease participants' distractions and increase immersion.

Simulation tasks We designed three tasks to highlight the educational goals.

In task 1, one should travel from earth to sun and back while focusing the time passing on earth, which will slow down while flying to the sun, but speeds up when traveling back to earth. The participants get informed, that the light takes approximately 8:20 min from sun to earth. Overall, when arriving back to

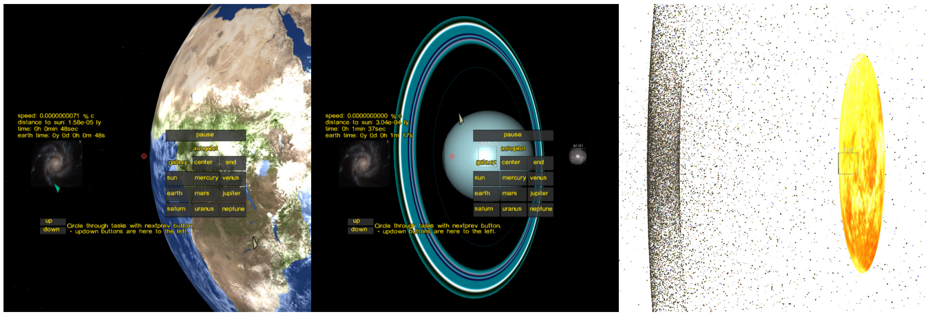

Fig. 1. Left picture: the cockpit view, including the autopilot, map, time and speed and the task bar. Middle picture: Uranus and its moon Ariel. The Lorentz contraction at a speed of $0.9999c$ flattening the spherical shape of the sun and the stars forming the galaxy in flight direction, while looking to the side. The background is color-reversed to raise the contrast.

earth, approximately 16 minutes have passed on earth, while just some seconds with the close-to-light-speed, underlining the twin paradox. Task 2 repeats task 1 on a massively different scale: The participant should fly to the center of the galaxy and back. Given a distance to the center of 50,000 ly, 100,000 years will have past on earth. In task 3, the participants should perform a proximity flight towards the sun, getting close and passing by. During the flight,they should direct their view on the sun, experiencing the Lorentz contraction on a spherical object, see right image in Fig. 1.

2.3 Questionnaire

Prior and post to the VLE experience, participants were required to complete a mandatory questionnaire that assessed the knowledge and immersive experience. For the Likert-scale questions on both questionnaires, we used items numbered from 0 - 4, with the key being "Not at all" (0), "Slightly" (1), "Moderately" (2), "Fairly" (3) and "Very much so" (4). A control question was incorporated.

Pre-questionnaire We collected the demographics, and Likert-scale questions *"How much do you think your education covered special relativity so far?"*, *"How well do you think you understand the basics of special relativity?"*, *"How well do you think you understand the principle of the twin paradox?"* and *"How well do you think you understand the principle of the Lorentz contraction aka length contraction?"*. In addition, we asked about the two common misconceptions of SRT: *"Moving clocks (regardless if coming closer or moving away) appear slower"* and *"Spheres under Lorentz contraction stay spheres."* Participants could answer with one of the following options: *"a true statement"*, *"a false statement"* or *"I don't know"*.

Post-questionnaire We repeated asking the two questions about the common misconceptions from the pre-questionnaire, and further on *"You are in a spaceship and attempt to fly in minimum time (!) from one end of the galaxy to the other. How long does it take you (you, not earth) if the galaxy's diameter is 100,000 light years? You can fly and accelerate as fast as you wish, not exceeding the speed of light."* with the options *"100,000 years"*, *"a bit under 100,000 years"*, *"instantaneous"*, *"never"* and the correct answer *"nearly instantaneous"*.

Then, we asked six consecutive questions regarding the twin paradox: *"Two spaceships are leaving earth in opposite directions: Ship A (your ship) and ship B. Both are flying with 90% of the speed of light for a month. From afar, you can observe a watch on B. Bs time is passing..."* (SRT1), *"To follow up to the last question: B is observing your watch as well and find out your watch is going..."* (SRT2), *"Continuing: B is still observing your watch and sees it:"* (SRT3), *"Now you brake hard, turn around and fly in B's direction, and with the same speed as B, keeping the distance. Once again, you are observing Bs watch and find, it is:"* (SRT4), *"B decides now to meet up with you again and brakes until you catch up (while you maintain your speed). During that phase, you take a look at Bs watch and see the time on B's watch is passing:"* (SRT5) and *"However, B checks your watch and finds the time on your watch is passing:"* (SRT6).

The answer options are (for all six questions the same): *"slower"*, *"faster"*, *"same speed as your time"*, *"at the beginning at the same speed, then faster"*, *"at the beginning at the same speed, then slower"*, *"at the beginning slower, then at the same speed"*, *"at the beginning faster, then at the same speed"*, *"at the beginning slower, then faster"* and *"at the beginning faster, then slower"*.

We consider the difficulty of this question-set as hard, but designed however, to rule out any trivial answers. To compare the results with a random answer sample: Given 9 possible answers per question, the average score results by picking randomly is $\frac{1}{9} = 0.111 = 11.1\%$ per question. Since the questions are consecutive, we anticipated a sequentially drop of correct answers.

Finally, we were asking immersive related questions [28, 23] for during and after the VLE experience. The questions for 'during' assessed competence, sensory and imaginative immersion, flow, tension/annoyance, challenge, negative affects and positive affects. The questionnaire regarding 'after' investigates basic attention, temporal dissociation, transportation, challenge, emotional involvement and enjoyment.

3 Tested group demographics

Our testing group had a size of n = 34 and one can see their demographics in Fig. 2. In average, every participant was going through all 4 steps in approx 40 min.

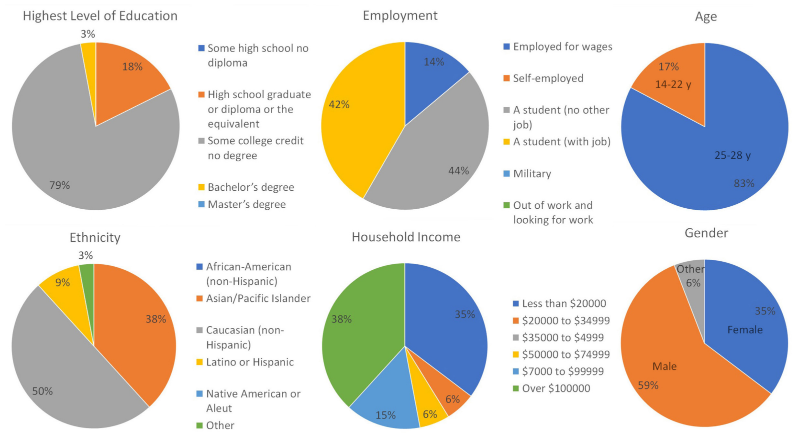

Fig. 2. Group demographics. The distribution of the participants age, level of education, employment status, ethnicity, gender and annual household income.

4 Results

Out of our testing group, 64.7% stated, that they had insufficient pre-education for understanding the SRT, 26.5% only a bit and 7.8% noted having been well educated for special relativity. This pre-education statement was not related to the actual existing knowledge, but rather about their secondary and partly tertiary education opportunities in SRT. 50% of the group did not understand the basics of SRT well prior. Within the other half, two participants stated to have profound knowledge about the topic, while the rest sees themselves on an immediate level. Only 17% claim to understand the twin paradox and the Lorentz contraction well and 20% to have some experience.

Evaluating the SRT myths, 29% believed incorrectly, that moving clocks, regardless of the flight direction, appear slower, and all of this subgroup stated to be equipped with pre-knowledge of the matter. The other 71% were uncertain of the answer. Among all participants, none believed the statement was false which was, in fact, the correct answer. This is a strong indication that many have either not been educated on the topic or hold an understanding of SRT that is incomplete. Lastly, 5.9% incorrectly believed that spheres remain spheres when undergoing the Lorentz Contraction while the rest said they did not know the answer.

The results of the SRT questions of the post-questionnaire can be seen in Fig. 3. The 'Moving Clocks' question could be clarified for 41% with a notable huge standard deviation (SD), while the second myth, the 'Spherical Shape' shows a definite improved results with 85% correct answers. Scores for the "Galaxy Travel" question scored lower in comparison. We believe this is because it requires participants to read the time displayed as text which was less visual and immersive for user. In future work, time displayed as text on the screen could be replaced by an analog clock to improve immersion and comprehension of the ideas presented in the simulation. Given the rudimentary knowledge of participants in this topic, our method could allow understanding of SRT to reach scores between $38 - 59\%$, see SRT questions 1 - 6 in Fig. 3. Since this questions are consecutive, the anticipated sequential score drop from SRT 1 to 6 is surprisingly not too pronounced.

Overall, the VLE experience significantly improved the understanding of SRT for our participants, given the facts, that (a) the group started in sum with minimal pre-knowledge, (b) the six consecutive SRT questions in the post-questionnaire are not answered in any material provided by us and must be derived from (the newly gained) understanding of the matter, (c) the six questions are directly challenging one of the SRT myths 'moving clocks are slower' which was shown in the pre-questionnaire to be a prevalent misconception among our participants, and finally (d) participants selecting randomly due to a lack of knowledge would result in scores in the rang of 11.1% when, it is evident, the scores are higher indicating at least an elementary knowledge of SRT.

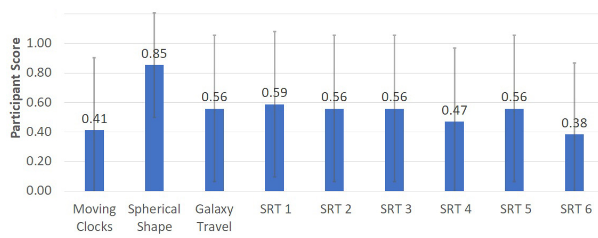

Fig. 3. Normalized, average score on SRT questions of the post-questionnaire.

In Fig. 4 the results of the assessment of the in-game experience felt during the VLE are shown in regards to seven components: Immersion, flow, competence, positive and negative affects, tension, and challenge. Each component is normalized to values between 0 and 1, where 0 indicates the lack of and 1 total agreement. The rating for positive affects was the highest with an average of over 0.8. The majority of participants enjoyed the simulation. This is underlined by the fact and in agreement with low scores in categories such as tension, annoyance and negative affects. We see the creation of a learning environment that ranks high in enjoyment as crucial for the learning process itself. Furthermore, the simulation did on average impose a low level of challenge (< 0.2) and this is despite the common difficulties known that students have with visualizations and the understanding of SRT. Overall, the users felt quite competent (> 0.7) and the scores for immersion and flow are very high (> 0.8 and > 0.65).

Our study has shown, that employing a real-time and real-scale VR-VLE as a teaching tool for SRT can offer learners enjoyment and a feeling of competence. We believe, that experiencing effects of special relativity in an immersive environment is an essential component for developing a deeper understanding.

Students were highly immersed in the gaming environment, they reported a loss of the connection with the outside world and a deep concentration on the VLE.

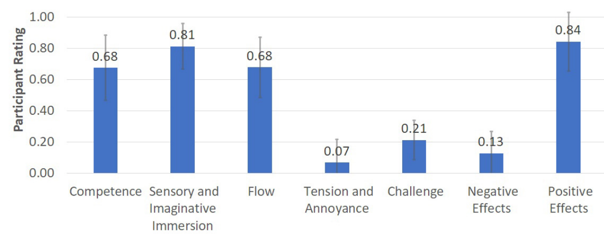

Fig. 4. Average rating of the immersion perceived during the VLE experience.

The evaluation of immersion after finishing the VLE can be seen in Fig 5. It aims to assess the varying degrees of attention in the first three items 'Basic attention', 'Temporal dissociation' and 'Transportation' as well as anxiety through challenge, emotional involvement and enjoyment [28]. It is very clear, that the challenge felt after the VLE ranks noticeable higher, than during their VLE experience, which is, based on several interviews later, based on the difficulty levels of the 6 SRT questions. However, this had limited impact on the overall enjoyment.

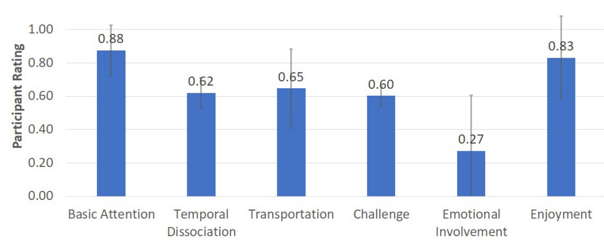

Fig. 5. Average rating of the immersion perceived after the VLE experience.

Upon further investigation, we split our group into two subgroups by their score on all nine SRT-related questions in the post-questionnaire and took a closer look at the upper third and lower third of scores. See Fig. 6 for the immersion assessed during and in Fig. 7 after the VLE. While several items got evaluated by both groups in similar ranges, and their difference becomes even less prominent in regards to the SD, the disparity for sensory and imaginative immersion with its lower SD in Fig. 6 is evident and is elevated for the lower third. The lower score on competence and the slightly higher one on challenge is, we believe intrinsic to participants who got exposed to SRT for the first time. Further on, there is a lower SD for basic attention, see Fig. 7, which we argue to be a result of less competence, but noticeable is also the higher overall enjoyment of the lower third of participants' scores.

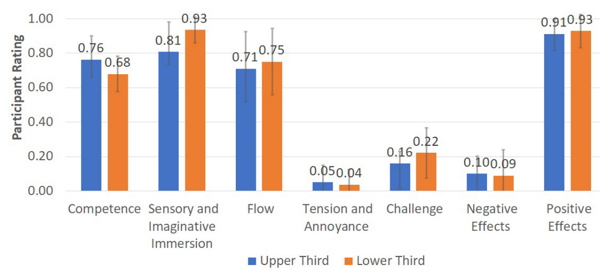

Fig. 6. Average rating of the immersion perceived during the VLE experience for participants who scored in the top (blue) and lower (orange) third.

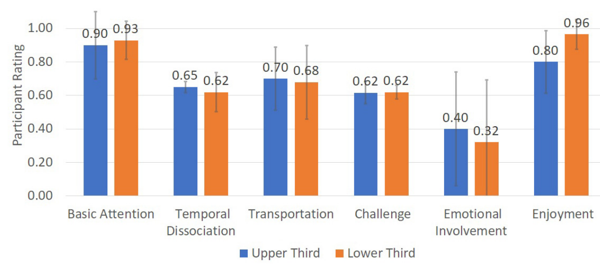

Fig. 7. Average rating of the immersion perceived after the VLE experience for participants who scored in the top (blue) and lower (orange) third.

Finally, we investigated the immersion for different improvement in the learning outcome. For that, we normalized the overall score of the nine SRT related questions of the post-questionnaire and subtracted a normalized factor derived from the four questions of their initial skills assessed by the pre-questionnaire. We split the participants into two groups again, focusing on the top and lower third in regards to improvement. See Fig. 8 for the participants immersion during and Fig. 9 post the VLE. Anxiety indicators 'tension and annoyance' and 'challenge' are elevated for participants, who were improving less, while most items in this figure are rather distinguishable by their SD, which is less widen for the 'most improved third'; a clear indicator for less frustration [23] and can also be seen in more basic attention and transportation in Fig. 9. At no point during the testing did we inform the participants whether or not their answers were correct. This leads to the expected conclusion, that participants who felt more anxiety improved less, but indicates a good validity of our measured data. However, overall the differences are not too distinct, which can be explained by the participants general enjoyment in Fig. 5 and positive affect score in Fig. 4.

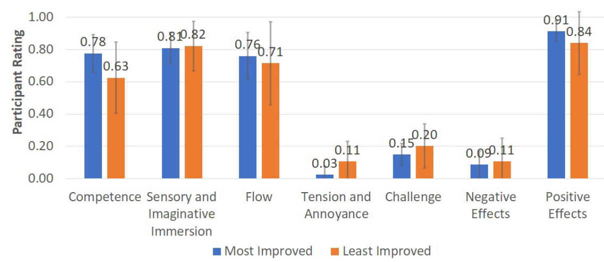

Fig. 8. Average rating of the immersion perceived during the VLE experience for participants who's score for improvement ranks in the top (blue) and lower (orange) third.

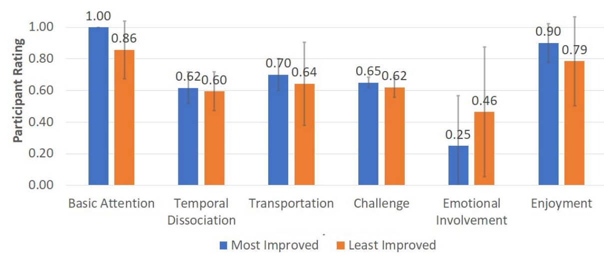

Fig. 9. Average rating of the immersion perceived after the VLE experience for participants who's score for improvement ranks in the top (blue) and lower (orange) third.

5 Conclusion

In our work, we have shown that an immersive and interactive real-time and real-scale special relativity simulation in virtual reality provides a high level of immersion and enjoyment and has a significant positive learning outcome. We tested participants prior- and post to the VLE experience and developed additional learning material to convey an abstract mindset for understanding the special relativity theory. Our results indicate, that visual reinforcement of objects under Lorentz contraction as well as several task to experience the twin paradox improved the knowledge and skills in special relativity for our tested group. With the Lorentz contraction being profoundly visibly pronounced in our VLE, in a high positive answer rate, and consequently learning success was observed. Time dilation effects, which were connected to a text-readout in our VLE, were measured with definite gain of skills as well, but can be further improved with a more visible representation. Further on, we evaluated the immersion during and after the VLE experience. The results indicate, that students were highly immersed in the gaming environment, they reported a loss of the connection with the outside world and a deep concentration on the VLE.

6 Future Work

Our VLE incorporated three tasks to solve, which were related to Lorentz contraction and the twin paradox. We believe, a gamification of these tasks with a positive/negative reinforcement can increase the immersion and consequently the learning outcome. Investigating into a direct comparison of two different version of our VLE, one with gaming elements, the other without, can lead to a better understanding of immersive learning in general.

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