An Immersive and Interactive Visualization of Gravitational Waves

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***Abstract*—In this work we are presenting a novel virtual learning environment for understanding the phenomena of gravitational waves. Emphasizing on the popular aspect of this topic, we developed an interactive and immersive gravitational wave simulation using a field density representation. We identified three main areas of understanding gravitational waves such as wave source, spatial irradiation distribution and wave type, which the virtual learning environment supports and was designed for. Participant were tested on their knowledge post and prior to the VLE experience as well as on their perceived immersion with the Game Experience Questionnaire. We found striking results in improving the understanding for gravitational waves, that underlines the feasibility of your virtual learning environment.**

***Index Terms*—Virtual Reality, Visualization, Virtual Learning Environment, Gravitational Waves**

I. Introduction

First discussed by Laplace in 1805 [1], proposed in 1905 by Henri Poincare [2] and predicted by Albert Einstein in 1916 [3], gravitational waves carry the gravitational force from accelerated objects. From general relativity, gravity can be expressed as space-time curvature caused by the presence of mass. Quadrupole accelerations of mass distributions will produce ripples in space-time [4]. These ripples propagate at the speed of light, and are known as gravitational waves. They were not widely studied until the 1950s, when it was proved by Hermann Bondi that gravitational waves are physically observable and in fact carry energy [5] [6]. The first confirmed evidence for gravitational waves, so far, was in in 1974: Russell Alan Hulse and Joseph Hooton Taylor, Jr discovered a binary pulsar system [7]. Over the course of the following 8 years, the loss of orbit distance of these pulsars was measured and satisfied Einsteins prediction precisely and was an indirect, calculated proof of the existence of gravitational waves [8], [9]. A Nobel Prize was awarded in 1993 for this discovery. For more than 20 years there were several ongoing efforts, but gravitational waves have not yet been directly detected until in 2015: The Laser Interferometer Gravitational-Wave Observatory (LIGO) at Cal Tech directly sensed the distortions in space time caused by passing gravitational waves generated by two colliding black holes nearly 1.3 billion light years away, gaining the general interest of the public [10], [11] [12].

Newton mechanics cannot predict gravitational waves, due to the instantaneous force distribution. According to general relativity, no force can expand faster than the speed of light which includes gravity [13] [14]. Under normal conditions, the distance to massive objects is relatively constant or subject to a linear velocity. Should a massive body change the distance to an observer regularly (sinusoidal or pulsating), would result in a periodical difference in gravity force [15]. Since the gravity force expanses with the speed of light, this periodical force shift propagates as waves. Moreover cosmological catastrophic events such as supernovae but also great moving masses can produce observable gravitational waves [16]. One common source are binary star systems, as was observed by LIGO, due to their orbit towards each other and the oscillating change of position relative to an outside observer in the orbit-plane.

The illustration of gravitational waves is subject of cosmology and theoretical physic lectures as well as popular science media in order to satisfy the general demand in exposition. The common methods are static images on whiteboards and visualized 3D simulations. Since in both cases depth impression is absence, the illustration is often reduced to a two dimensional representation in order to not overload the visuals. Furthermore the absence of interactivity is evident. Virtual Reality (VR) makes it possible to immerse the learner into a Virtual Learning Environment (VLE) [17] [18] [19] that is enhancing, motivating and stimulating learners' understanding of certain events [20] [21]. Interactive VLE's have shown the ability to transmit physical phenomena surpassing traditional learning methods [22] [23]

Our novel VLE approach utilized virtual reality (VR) and interactivity to maximize the immersion and consequently the learning effect. In order to gain meaningful data and evidence of effectiveness, we identified three main areas of gravitational waves which encompass a broad and general understanding of the phenomena: Source of gravitational waves, their spherical distribution from the source and the wave type. As for the source, we have chosen a binary star system, as gravity waves are easy explained by such an oscillating configuration rather than a single event. In order to fully understand gravitational waves, it is imperative to recognise the distribution direction, which in case of a binary star system settles its maximum amplitude along the plane, which is spanned by the two rotating stars. Solutions to Einsteins gravitational wave equations are transverse wave ripples, which the VLE must support to easy identify.

II. Methodology

The gravitational force is described as a vector field consisting of a weighted vectors for every point in space. Early testing showed, that the presentation of a regular vector grid in VR is overly complex and hard to get immersed into. Other attempts with color coding the strength of the gravitational force in addition to the directional vector showed similar weak results. To illustrate the gravitational waves, we rather decided to use a density grid: regular points in space, which are connected in x, y and z- direction and are warped due to gravitational forces.

To further improve the understanding we decided to add representations of the earth with an orbiting moon to show familiar objects the participants can relate to, as they are as well as the density field exposed to our generated gravitational waves. In the VLE the participants can also observe a two star binary system which represents the source of gravitational waves. Using a real scale environment, it becomes apparent that the distances of the solar objects are too great to be visible in one scene, therefore we decided to use an observable, artificial scale. This allows us to show all objects, such as planet Earth, the moon and the source of the gravitational waves, the binary system, in one observable scene. This way, participants are able to derive correct conclusions about the nature, origin and impact of gravitational waves. All stellar objects also display their gravitational effects in the density grid.

To calculate the gravitational wave effect of the binary system on space, we start from the flat space field equation (constant in time)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{1}$$

with additional small deviations h from that flat space

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \tag{2}$$

with the wave equation

$$[\partial^2 h]_{\mu\nu} = 0. \tag{3}$$

Solutions to Einstein's equations show that a gravitational wave metric oscillates sinusoidal:

$$h_{\mu\nu}(t, z) = h_{\mu\nu}{}^0 sin(k(t - z)). \tag{4}$$

Given a moving gravitational wave along the z-axis, planes in xy experience different values for different times t, which make the wave transferal, as the metric shows:

$$\begin{aligned} g_{xx} &= 1 + h_{xx} \\ g_{yy} &= 1 - h_{xx}. \end{aligned} \tag{5}$$

We pre-calculated the wave distribution for one period of the binary stars and stored this in an array (wave-array) on the GPU. Since the torque stays constant, meaning frequency and distance are inversely proportional, changing the torque would result in a change of amplitude. Different frequencies can also be handled by scaling the wave-array. As long as the masses of the binary star system stay constant, this pre-calculated wave-array passes within reason correct values for a qualitative meaningful observation. Due to the extended GPU shader work, we used OpenGL for the graphics API and OpenVR as VR library. Our testing took place on a Windows PC with an AMD Ryzen 7, an NVidia GTX Titan V graphic card and HTC Vive Pro Eye as our HMD.

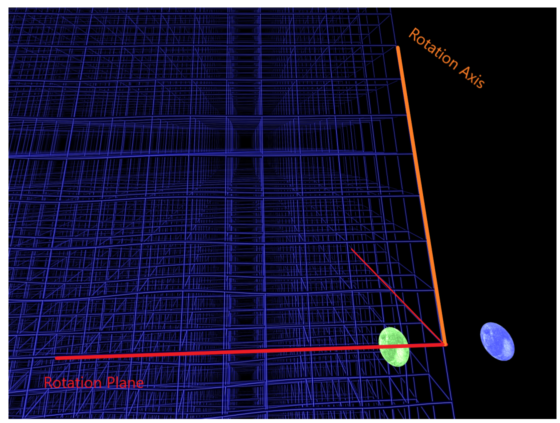

Fig. 1: The image used to indicate possible answers for question #5.

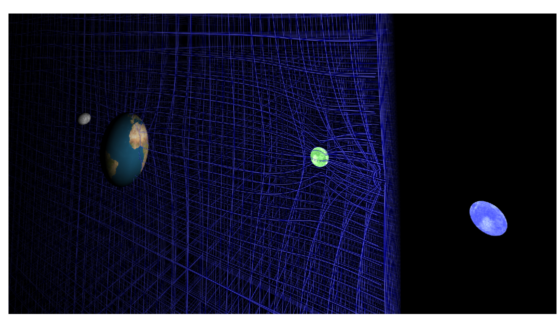

Fig. 2: VLE scene near binary stars with a heavily distorted density grid because of the stars masses.

The VLE environment consists of the planet Earth, the orbiting moon, and the binary star system which rotates around the y-axis and oscillates in the xz plane. A density grid is applied to one quarter of the plane, crossing through it in y-direction. This setup lets the VLE participant observe the Earth extending half way out of the grid, as well as the binary system crossing the grid for one quarter. This quartered representation is necessary in order not to overload the visual representation and obstruct the view on the objects. The participants are able to freely move around the x-y plane with the touch pad of a VR controller and can per request also change the position up and down on the y axis. Moreover and most importantly, the controller can be used to measure the current wave-effect-magnitude on every point in space. This setup lets the participant experience the uneven wave distribution around the wave-source, which focuses its maximum magnitude on the xz-plane. Additional to the gravitational waves traveling through the density grid, each stellar object in the scene displays their respective gravity as well, in order to make the distinction between gravity and gravitational waves unambiguous. The density grid consists of a three dimensional line grid rendered in OpenGL using vertex, geometry and fragment shaders to create a billboard like laser representation of each grid line. In order to create a decent and smooth behaviour of the density grid in regards of gravity and also gravitational waves representation, the grid was subdivided in 10 sections between each line intersection, which in turn is being separately distorted by gravity and gravitational waves respectively. In order to let each separate grid point be influenced by every object and also the gravitational waves effect, we created a distortion function inside the vertex shader that calculates a distance to each stellar object and adds a displacement to the initial position depending on the squared distance and mass factor of each object. For a more realistic representation of the gravity behaviour of earth, moon and the binary stars we also included a maximum displacement function to make the grid stop on the surface of each body and wrap around it. For an even more in depth impression of the influence of gravitational waves we also decided to let the model of earth be deformed according to the current magnitude of the waves effect at earths position. In order to give the participant the ability to measure the gravitational waves magnitude numerically at each point in the represented space time grid, additionally to the visual impression, we utilized compute shader. This shader calculated the same displacement that gets added for each grid element but for the current position of the controller and writes this value on a shared buffer array, which gets in turn read by the GPU. From there it is again sent to the GPU into another billboard render to display it visually slightly above the controller. Moreover we added a gauge representation that would move an indicator according to the measured value.

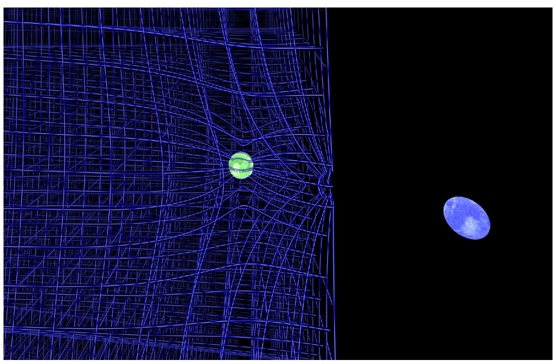

Fig. 3: The binary stars as source of gravitational waves in the VLE.

To measure a gain in understanding, we let the group of participants complete a pre-questionnaire and post-questionnaire (see Section III), respectively before and after the VLE experience. During the VLE experience the participants have to finish two tasks:

1. Measure different areas for their wave-amplitude around the binary star system to illustrate the irradiation distribution. Find the area that is most affected by the waves effect.

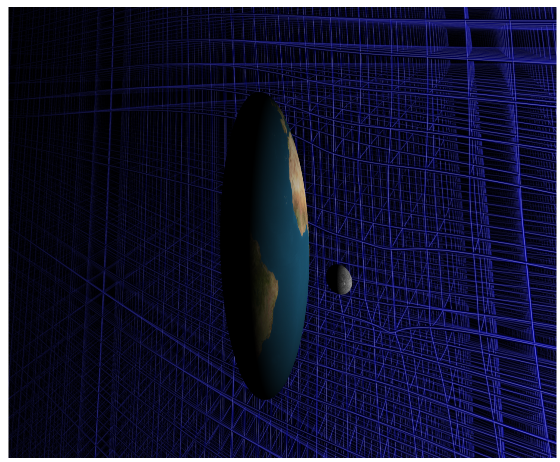

Fig. 4: Representation of earth with orbiting moon in the space time grid. Everything under the effect of gravitational waves at one point in time.

2. Change the distance and period-time of the binary star system and observe the change of gravitational wave-magnitude and distribution. The goal is to illustrate the linear dependency of wave-amplitude and torque.

These tasks were laid out to lead the participants to find the answers to our research questions as seen in Section III and especially understand why the answers are right.

III. Questionnaire

In order to asses the participants change in understanding of gravitational waves, we required everyone to complete a pre and post survey before and after the VLE experience. To evaluate previous and gained knowledge we designed five questions as follows

1. What type of waves are gravitational waves?
2. How does the magnitude of the gravitational waves effect change if the radius between the rotating stars changes?
3. What happens to a distant planet if the two stars collide, merge and would be on one place?

4. How does the magnitude of the gravitational wave effect change if the rotation speed of the rotating stars changes?

5. Which area in space time is most affected by the gravitational waves effect?

Each participant was asked to answer to the best of their knowledge in each of the questionnaires. For question #1 and #5 we also added visual representation of the questions topic in order to make them easier to grasp. In particular, for question #1 we added a moving representation of transverse and longitudinal waves because we found that most participants were familiar with the terms but could not describe them accurately. As question #5 can also be solved with the VLE, we decided to include a screenshot of our scene. Each question had at least five possible answers with the majority of them having the option "I do not know" to reduce the occurrence of participants choosing the correct answer by chance. We added this option after the first five participants mentioned that for some of the questions it was pure guessing. In addition to the five questions the post questionnaire also assessed the immersion "during" the VLE in regards to competence, sensory and imaginative immersion, flow, tension or annoyance, challenge and positive or negative effects, as well as "after" the experience with attributes attention, temporal dissociation, transportation, emotional involvement, challenge and enjoyment.

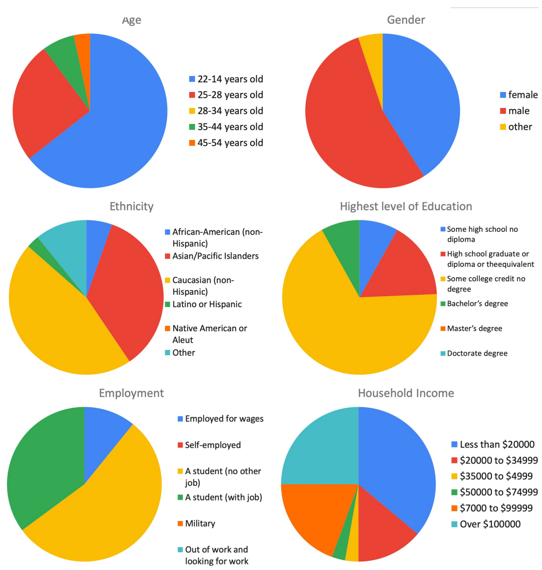

Fig. 5: Group demographics. The distribution of the participants age, level of education, employment status, ethnicity, gender and annual household income.

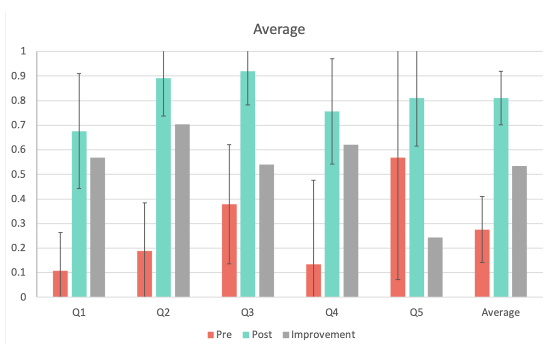

Fig. 6: Result score for each question and all participants: (orange) pre- and (cyan) post-questionnaire. (grey) improvement.

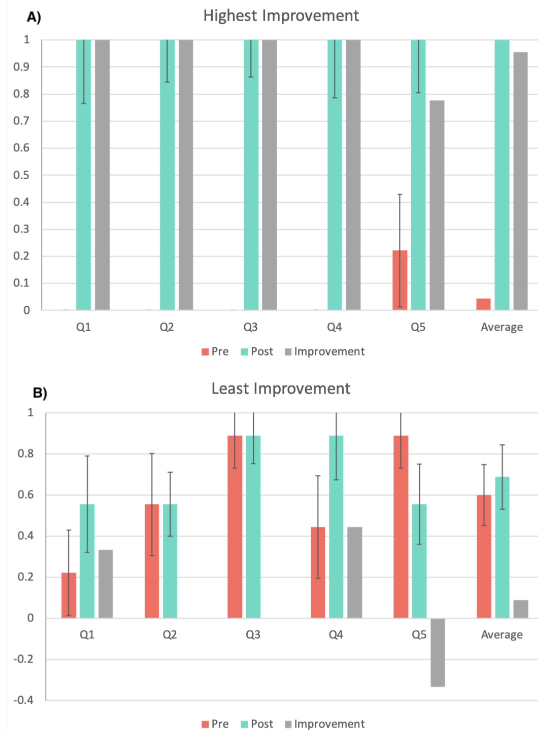

Fig. 7: Result scores for participants that improved the most and least after the VLE: (orange) pre- and (cyan) post-questionnaire. (grey) improvement.

IV. Tested Group Demographics

Our tested group consisted of n = 35 and their demographics details assessed in the questionnaire are visualized in Fig. 5. Every participant went through the given tasks and questionnaires in approximately 20 minutes.

V. Results

A. Research question response evaluation

The acquired data showed a striking increase in understanding of our proposed research questions. As seen in Fig. 6 already the average amount of each separate question for all participants shows an eminent gain of positive responses after the exploration of our simulation scene. The right column displays the average for all questions and supports the first insight. We calculated a value of 27.56% correctly chosen answers before the VLE and 81.08% afterwards, which sums up to an increase of even more than 50% what we expected. Especially question #2 "How does the magnitude of the gravitational waves effect change if the radius between the rotating stars changes?" seems to be the least intuitive for

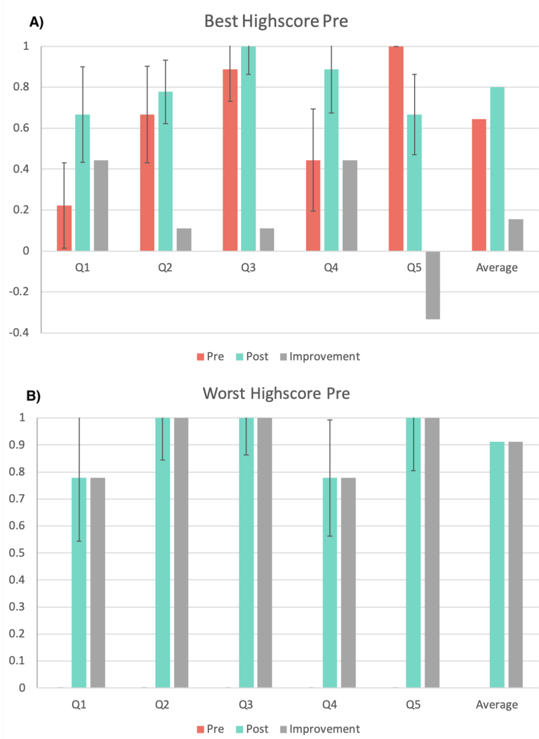

Fig. 8: Result scores for participants that showed the highest and lowest score before the VLE: (orange) pre- and (cyan) post-questionnaire. (grey) improvement.

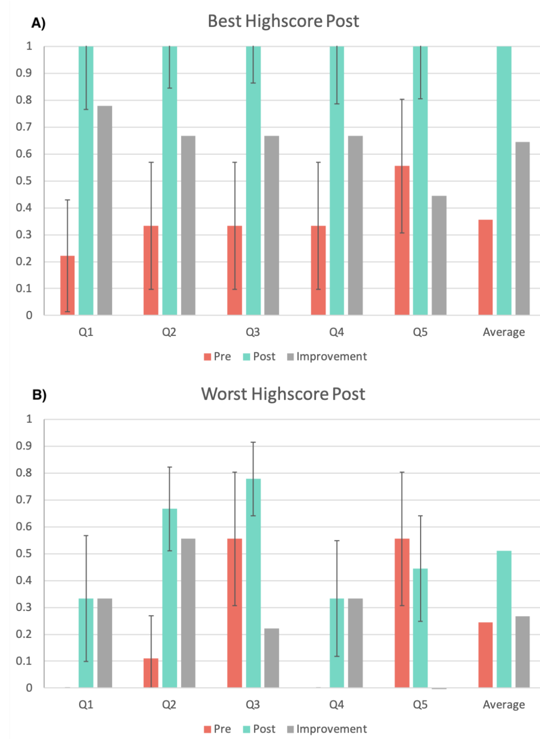

Fig. 9: Result scores for participants that showed the highest and lowest score after the VLE: (orange) pre- and (cyan) post-questionnaire. (grey) improvement.

most participants before seeing the simulation and therefore shows the highest percentage gain. This assumption also got confirmed by verbal feedback of multiple participants that stated that their intuition had told them the exact opposite of what happened in the simulation regarding this attribute of the rotating stars. It is also worth mentioning that for many participants the two different type of waves were not entirely clear, even with the displayed visual representation, which most likely lead to some slight skew in the collected results of question #1. All groups of best or worst participants in the following section concern the upper or lower third respectively of the overall data set in regards to the currently discussed attribute.

Fig. 7 (a) illustrates a striking difference in the ratio of correct to wrong answers, especially for the subgroup of participants that on average improved themselves the most. This leads to the insight that especially people who have barely any or a wrong understanding of the research topic can benefit extensively from our representation. This is also confirmed in the Fig. 7 (b) as it shows that the part of our group who scored the lowest in the pre-survey also indicated a very high improvement in their respective post questionnaire answers. Four out of five questions showed improved outcomes even for participants with already comparably good prior understanding as seen in Fig. 7 (b). Only one of the questions showed a slight decrease in correct answers, but as question five (#5) shows the only negative development (also seen in Fig. 8 (b)),

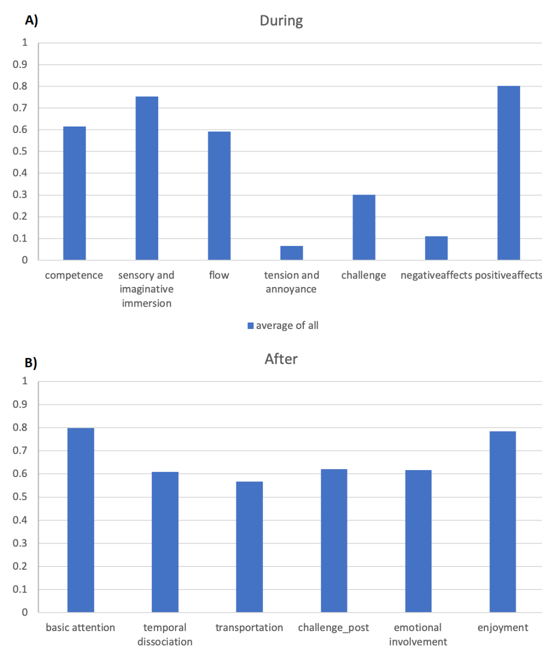

Fig. 10: Immersion level for all participants during and after the VLE. Each value is in the range from 0 (not at all) to 1 (absolutely).

we concluded that the missing "I don't know" choice for this answer increased the random noise and therefore diminished the overall outcome. As the group with best pre-questionnaire score results and least improvement are most probably the same participants for the biggest part, we can see a very similar pattern in both mentioned figures. The results shown

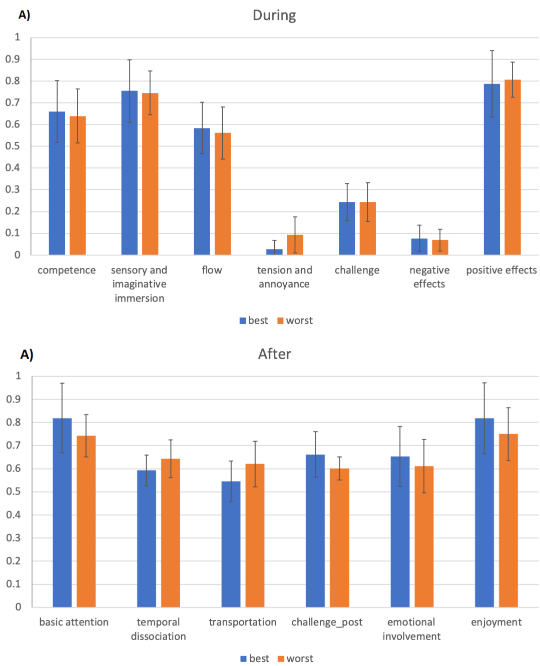

Fig. 11: Immersion level for participants that showed the highest and lowest score before the VLE. Each value is in the range from 0 (not at all) to 1 (absolutely): (blue) best- and (orange) worst third scored participants.

in Fig. 8 clearly identify a confirmation for the previously taken assumption in Fig. 7, as it displays the results for the group of participants that chose the least correct answers prior to the VLE experience with a very similar pattern. What is especially notable here: even participants, which apparently did not have a fitting impression of the gravitational waves effect prior, could achieve an even slightly better score than average post experience score.

It is also worth noting that even the group of participants with the lowest average of correctly chosen answers after experiencing the VLE still show an extraordinary improvement of 30%.

B. Immersion values evaluation

Conducting the Game Experience Questionnaire, we assessed the immersion during the VLE experience followed by the Game Immersion Questionnaire measuring the immersion felt after the testing. Fig. 10 (a) shows that even some of the participants seemed to feel not overly competent in finishing the given tasks of finding answers to the respective research questions, on average they were still positively affected and stated a high sensory and imaginative immersion. Part (b) in the same figure suggests that participants were overall still trying their best to achieve the necessary knowledge to find the correct answers and enjoyed the simulation, even though they felt challenged by it. It is notable that on average the participants were stating to feel less challenged during the experience than afterwards, which is probably caused by the difficulty of answering the research questions and remembering the gained impressions of the VLE. According to verbal feedback many participants were also slightly overwhelmed by processing the gained information during and after the VLE experience.

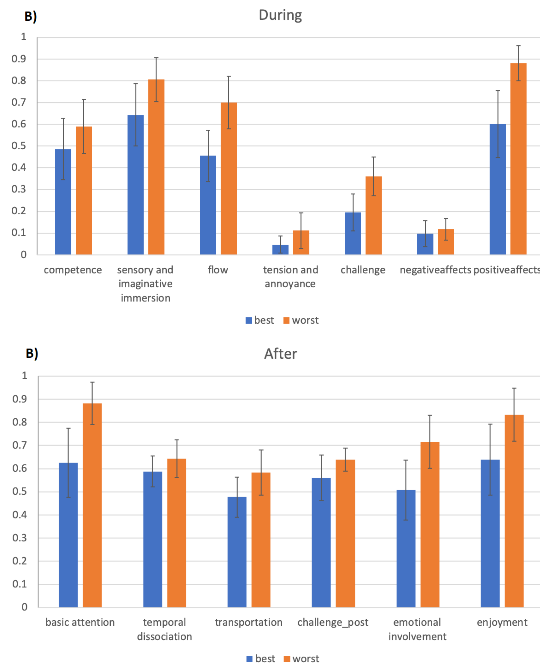

Fig. 12: Immersion level for participants that showed the highest and lowest improvement after the VLE. Each value is in the range from 0 (not at all) to 1 (absolutely): (blue) best- and (orange) worst third improvement outcome of all participants.

Comparing the immersive responses of best and worst scoring participants of the pre-questionnaire as can be seen in Fig. 11, even seemingly big differences in previous knowledge and understanding does not influence the immersive impressions of the participants in a significant manner. What is remarkable is to compare the stated challenged feeling for both groups during and after the VLE experience is approximately the same. This suggests that participants with a high pre-questionnaire score felt equally challenged with the simulation, even though they already brought some comparably good understanding of the subject. We assume this is because most participants were not aware of their correct perception, as they were only told the correct results after finishing the post questionnaire.

We identified a noteworthy tendency about participants who achieved the worst score post VLE to state overall higher immersive involvement than their best scoring counterpart, as can be seen in In Fig. 12. Moreover, the stated feeling of higher competence and given attention to fulfilling the tasks is remarkable, as the outcome of the research question evaluation would suggest the opposite. Observation of the participants during the VRLE and verbal feedback indicated that some participants got distracted of the actual task at hand and therefore from interpreting the scenery and its information by the strongly moving and colorful scenery. This could be the cause for the overall lower score of the participants that still stated a higher than average enjoyment, emotional involvement as well as attention afterwards.

VI. Conclusion and Future Work

We developed a virtual learning environment to convey the subject of gravitational waves. Identifying three areas of study: wave source, spatial irradiation distribution and wave type, we conducted a pre- and post VLE experience questionnaire as well as measuring the perceived immersion. We achieved striking results in transmitting the subject matter as the results of our analysis on understanding of popular science level gravitational waves conclude. We have successfully shown, that our immersive and interactive representation of this highly complex physics topic can be used to enhance the understanding of gravitational waves.

Future work encompasses a further expand into gravitational waves, such as the simulated event from 2016, when a binary black hole system collapsed.

Acknowledgment

This section is left blank for the plenty of acknowledgment we plan to write down for all the participants, and helpers who made this study possible. For reasons of anonymization, we leave this "blank" for now. This section is left blank for the plenty of acknowledgment we plan to write down for all the participants, and helpers who made this study possible. For reasons of anonymization, we leave this "blank" for now.

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