Immersive Learning for Scale and Order of Magnitude in Newtonian Mechanics

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Abstract. The purpose of this paper is to gain a better understanding on the role of immersive learning in regards to one's intuition on the order of magnitude and scale, by using projectile motion as an example of Newton mechanics. We developed a semi-tangible virtual reality (VR) application that serves as virtual learning environment (VLE). In this application, participants throw objects and explore the effects of different conditions, such as variations in gravity and air density. A questionnaire was conducted prior to and following the VR experience. Its purpose was to assess the participant's skill in estimating an object's behavior in varying conditions and their perception of the immersive experience. The VLE aimed to immersively train the participants to improve their perception of the scale and order of magnitude of key variables in Newtonian Physics. Our studies have shown that a semi-tangible virtual reality application improves the intuition of the scale and order of magnitude for the given Newtonian sample system and provide a highly immersive experience.

Keywords: Immersive Learning · Newton · Newtonian Mechanics · Order of Magnitude · Scale · Perspective · Virtual · Reality · Learning · Environment · VR · VLE

1 Introduction

To gain an understanding for scale and order of magnitude in Newtonian mechanics, deep-seated preconceptions that conflict with classical instructions have been reported [1]. Learners tend to hold scientifically incorrect ideas about physics concepts in general, and about force and motion concepts in particular. The conceptual difficulties in mechanics have been well documented [12] [14] [15] [22] and a considerable body of literature in science education has been formed [16] [20] [21]. To overcome the limitation of current immersive experience in a typical classroom setup, there have been various attempts to create a virtual learning environment (VLE) regarding Newton mechanics. 2D approaches, such as *Newtons Playground* [18] or 3D applications, such as *Physicss Playground* [19] that exploit the strengths of our immersive virtual environment, or *NewtonWorld*, a collection of virtual worlds designed to explore the potential utility of physical immersion and multi-sensory perception to enhance science education [13] found significant pretestposttest physics gains and have been studied thoroughly [17]. Nowadays VLE's aim to add intuitive understanding of Newton mechanics by immersing the learner in order to enhance, motivate, and stimulate learners' understanding of certain mechanics [3] [4]. Carefully designed physics simulations can even offer a level of comprehension that exceeds an understanding built during a traditional physics course [5].

This work aims to measure learning outcomes and the entanglement with immersion by investigating competence improvements in intuition and abstraction regarding scale and order of magnitude. For that, a VLE was created which lets participants throw an object of a certain mass under different settings of gravity and air-density. A pre- and post application test examining their skills was conducted. The VLE aims to train the learner to deduct a better result on the post-questionnaire, rather than directly leading to correct answers.

To enhance the immersion, VR was being used in combination with a haptic controller for throwing the object, a ball, making it necessary to perform a real object-throwing body movement. Such pedagogical design elements were described and analyzed well to create a process of structuring learning situations that create constructivist experiences [24]. According to Desai, S. et.al. tangible systems are less complex to use and they require less time to encode and retrieve associated knowledge to use them intuitively. They are associated with low domain transfer distance and easy discoverable features [23].

To assess the immersion during the VLE experience, different metrics have been explored such as eye-tracking methodologies [10], subjective approaches [9] and non-interactive [6]. Questionnaires are used in this work to measure immersion in interactive media [8] and provide a good framework of testing participants of a VLE. [7] [11].

2 Methodology

We tested our VLE on 33 participants. By conducting our research in three different steps we were able to accurately track the immersive learning effect on the participants. We began by having the user take a survey to collect demographic information and a quiz to get a baseline reading for their understanding of Newtonian mechanics (step 1). The quiz was followed by the VR application (step 2), and finally a post application survey (step 3).

For this research, we developed a model for users to learn about gravity and surface pressure. This model consisted of five environments with different conditions. By altering the gravity and surface pressure in each environment, the application lets the participants explore different conditions and learn about the scale and order of magnitude in Newtonian mechanics. In comparison to other applications on two-dimensional screens, ours used realistic environments and a first person point of view. Further on, by utilizing a head mounted display (HMD) and touch sensors, participants were able to move their head freely and use virtual hands to interact with the application.

Prior to and immediately following the VR experience, participants were required to complete a survey that analyzed their user experience and tested their knowledge regarding the scale and order of magnitude of Newtonian mechanics for various kinematic variables. Furthermore, the survey gathered data about the immersion felt by users during and after the VLE.

2.1 Baseline Data Collection

First, we needed to get an initial reading of the user's perceived expertise and their actual expertise on the topic of Newtonian mechanics. We achieved this goal in the form of a quiz consisting of ten questions, where users would estimate the distance a ball would travel under different conditions. Participants were provided with an initial environment to compare to the question environments, but were not given any information about how gravity and surface pressure affect projectiles.

2.2 Application

Development Our application transports participants to five different planetary bodies. Four of these environments are based on realistic locations in our solar system. See Table 1. One environment was reserved as a sandbox environment where users could adjust the gravity and surface pressure themselves, allowing the user to explore different combinations.

Planetary Body	Gravity	Surface Pressure
Earth	9.8 m/s^2	1 bar
Earth's Moon	1.6 m/s^2	0 bar
Mars	3.7 m/s^2	0.01 bar
Pluto	0.7 m/s^2	0.00001 bar

Table 1. The four environments participants could explore in the application and their corresponding gravity and surface pressure.

The application was developed using Unity, C#, and the Oculus Rift, including their touch sensors. The Unity Asset Store allowed us to easily immerse our users with realistic landscapes. See Fig. 1. C# scripts allowed participants to record and display the information about each throw, switch scenes without breaking immersion, have unlimited ball throws, and change the environmental settings. The users were able to modify the gravity to any value between .001 m/s^2 and 20 m/s^2 and the surface pressure to any value between 0 bar and 10 bar. To calculate the exact distance a ball was thrown, we took the difference between the position of the ball as it leaves the user's hand and the position when the ball collides with the ground.

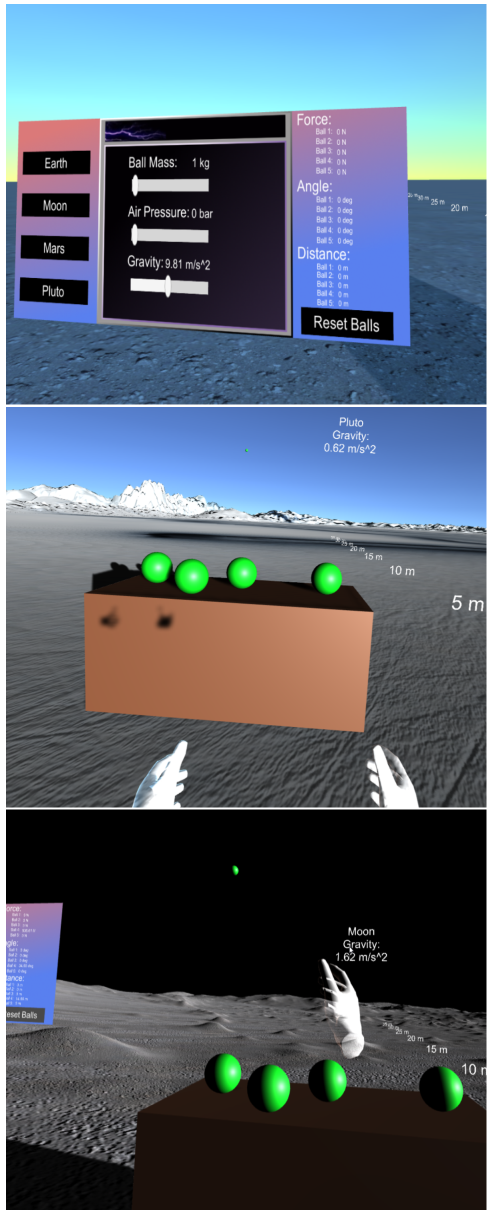

Fig. 1. Application photos. (Top) U.I. board for displaying throw information, sliders to adjust sandbox environment variables, and buttons for switching environments. (Middle) A user preparing to throw a ball on Pluto. (Bottom) A user observing their ball toss on the Moon.

Notably, the immersion wouldn't be possible without the HMD attached touch sensors. VR is an important component to this project because the first person perspective of the environment enabled users to better experience the effects of gravity and surface pressure at different orders of magnitude. The HMD and touch sensors gave our users the ability to grab and release balls by making a fist and looking around the scene by rotating their head. To exert a throwing force on the ball the users had to physically replicate a throwing motion with the touch sensors.

Application Tasks We designed three tasks for our participants to accomplish in the application. The goal of these tasks was to help the users learn how the scale and order of magnitude of gravity and surface pressure affect the distance a projectile will travel.

To do this we had the user begin Task 1 in a familiar environment (Earth) and pick up balls with the Oculus touch sensors. The participants would then throw balls until they were approximately throwing at a 45 degree angle, with a flight distance of 4.6m. At this point we determined that the participants were comfortable in the application and able to reliably throw the balls.

Task 2 directed the users to proceed to the next environment, the Moon. The participants would then throw all five balls and observe the distance they traveled. The participants then repeat this process on Mars and Pluto.

Task 3 instructed the user to travel to the sandbox environment and throw balls to notice if the distance and trajectory of the ball resembles any environment they had already been in. After a few throws they would change the environmental variables and repeat the process until they had thrown balls in environments with high, medium, and low gravity and with high, medium, and low surface pressure.

2.3 Questionnaire

Before and directly after step 2, participants were required to complete a mandatory questionnaire approved by the Cal Poly Institutional Review Board. We used unique identifiers to link user's surveys without compromising their anonymity. To survey the user's immersive experience, we utilized the Likert-scale. The scale numbered responses from 0 - 4, with the key being "Not at all" (0), "Slightly" (1), "Moderately" (2), "Fairly" (3) and "Extremely" (4).

Initial Survey In the initial survey, we asked a single Likert-scale question to gauge participant's self-perceived understanding of Newtonian mechanics. We also collected participant's demographic info.

We then asked ten questions regarding the distance a ball will travel under different orders of magnitude of both gravity and surface pressure. The velocity of the ball, the launch angle, and the mass of the ball were constant throughout each question, but the environmental variables, gravity and surface pressure, would vary. Notably, we gave the participants the horizontal distance a ball would travel for an example situation with the following conditions: $F_{grav} = 9.8m/s^2$

$P_{sp} = 1bar$ Users were then instructed to answer the following questions: How far would the mass travel if launched at a 45 degree angle at $7.0m/s^2$ on...

1. Venus? (gravity: 8.87 m/s^2, surface pressure: 92 bar)
2. Mercury? (gravity: 3.7 m/s^2, surface pressure: 0 bar)
3. Titan? (gravity: 1.352 m/s^2, surface pressure: 0 bar)
4. Carme? (gravity: 0.17 m/s^2, surface pressure: 0 bar)
5. 55 Cancri e? (gravity: 78.3 m/s^2, surface pressure: 0 bar)
6. Neptune at high altitude? (gravity: 11 m/s^2, surface pressure: 30 bar)
7. an Earth-sized planet with high atmospheric pressure? (gravity: 9.8 m/s^2, surface pressure: 20 bar)
8. on a Mercury-sized planet with high atmospheric pressure? (gravity: 3.7 m/s^2, surface pressure: 20 bar)
9. a Carme-sized planet with high atmospheric pressure? (gravity: 0.1 m/s^2, surface pressure: 20 bar)
10. a Earth-sized planet with twice the gravitational pull? (gravity: 18.2 m/s^2, surface pressure: 1 bar)

2.4 Calculating Survey Question Answers

Our goal with this study was to create a VLE rather than a true simulation of Newtonian mechanics on different planetary bodies, so we let some aspects remain constant throughout the experiment. For our question results, we set the temperature and viscosity for each environment as a constant. We assumed a temperature of 25 Celsius, and an absolute viscosity to be $\sim 1.810^{-5}$Ns/m^2. Selecting these to be constants gave us a dynamic friction coefficient C_d of 0.5 on the ball for each environments. For each question we also kept the following constants in order to measure strictly the user's understanding of how gravity and surface pressure affect the distance a ball travels. $m_{ball} = 1.0kg$ $v_i = 7.0m/s^2$ $\Theta = 45.0°$

Post-Survey Immediately following the VLE, participants were required to complete a survey that analyzed their experience, and then given the same quiz as at the pre-questionnaire.

3 Participant Demographics

The initial survey collected participant's demographic information such as age group, location, gender, ethnicity, highest education, annual household income, employment, and marital status. We found that 64% of our participants were male and 36% were female. 88% of our participants were pursuing a college degree and 70% of our participants make less than $20,000 annually. For age, level of education, employment status and ethnicity, see Fig. 2.

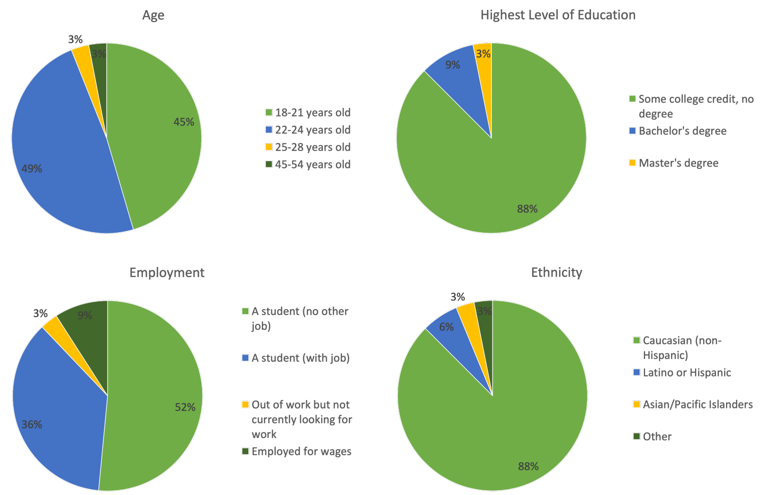

Fig. 2. Participant demographics. The distribution of the participants age, level of education, employment status, and ethnicity.

4 Results

On average, participants rated themselves a 1.96 on a scale of 0 to 4 when describing their understanding of Newtonian mechanics (0 indicating a lack of understanding and 4 complete understanding). Comparing the results of the initial quiz to the final quiz we found that 76% of participants made more accurate estimations after using the VR application.

Table 2. Distribution Frequencies and Test Hypothesis Probabilities

Level	Count	Probability	Hypothesis Probability
Didn't Show Learning	116	0.35152	0.50000
Showed Learning	214	0.64848	0.50000
Total	330	1.00000	1.00000

Binomial

Distribution of Survey Results. Of the total 330 questions asked, 215 questions improvement from the initial survey to the final survey.

When examining question results, we compared the difference between the initial estimate and final estimate to the calculated expected value. We defined a guess that "showed learning" as one where the difference between their guess and the expected value decreased after using the application. A guess that "did not show learning" was one that grew farther away from the expected value after using the application. By classifying the quiz estimations in this way, each

Table 3. Binomial Test

Binomial Test	Level Tested	Hypothesis Probability (p1)	p-value
Ha: Prob (p > p1)	Showed Learning	0.50000	**<.0001***

question was reduced to one of two possible outcomes; "showed learning or "did not show learning. We saw a participant's estimation for each question as independent from each other because each question was unique. Thus, we were able to create a Binomial Distribution of the data. Our null hypothesis was that our VLE does not help one understand the scale and order of magnitude in Newtonian mechanics. We set our hypothesis probability to 0.5, and calculated an exact one-sided binomial test that looked for a probability greater than the hypothesized value. This resulted in a p-value of <.0001. Since our p-value is less than 0.05 we were able to reject our null hypothesis and state that there is enough evidence to suggest that the alternative hypothesis, that our VLE does help one understand the scale and order of magnitude in Newtonian mechanics, in particular projectile trajectory, can be accepted.

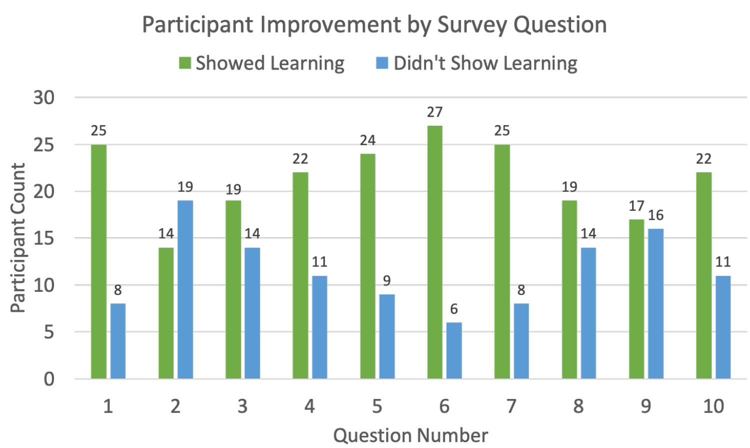

Fig. 3. Survey Improvement Results

We also calculated a binomial distribution for each question individually, see Fig. 3. We assumed the same null hypothesis as before, that Virtual Reality does not help one understand scale and order of magnitude in Newtonian mechanics and set our hypothesis probability to 0.5. Then calculated an exact one-sided binomial test, that looked for a probability greater than the hypothesized value. We calculated the test probabilities and got the following p-values respectively for questions 1 through 10: (0.0023, 0.8519, 0.2434, 0.0401, 0.0068, 0.002, 0.0023, 0.2434, 0.5, 0.0401). Since our p-value is less than 0.05 for questions 1, 4, 5, 6, 7, and 10 we were able to reject our null hypothesis for those questions. This suggests that the alternative hypothesis, the VLE does help one understand the scale and order of magnitude in Newtonian mechanics, can be accepted. Questions 2, 3, 8, and 9 resulted in p-values > 0.05 and we were unable to reject the null hypothesis. We expect this behavior is because our participants initially guessed close to the calculated value for questions 2 and 3. We attribute the p-values of questions 8 and 9 to the underestimated effects of surface pressure in high-pressure environments.

An additional way we examined the quiz result data was through the average bounded difference between the estimates and the expected value. Because of the high variability in the order of magnitude from participant to participant in this application, extreme outliers were not uncommon and would greatly modify the average estimate for each question. In order to account for these outliers, we used the following approach: $diff = |actualvalue - median|$, $UpperBound = median + (2 * diff)$, and $LowerBound = median - (2 * diff)$ We took the absolute value of the difference between the median of the estimates for that question and the actual value. Next, for any outlier that was outside of the calculated UpperBound or LowerBound we snapped it to the bound it was closest to.

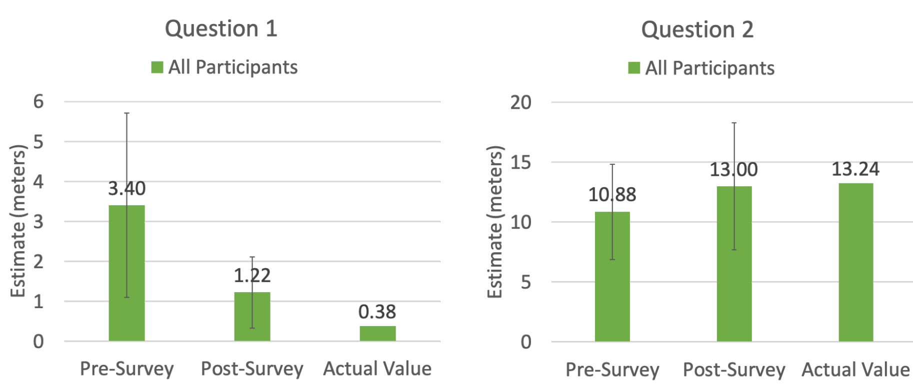

Fig. 4. The Average Bounded Response of Questions 1 and 2.

In Fig. 4, Fig. 5, Fig. 6, and Fig. 7 you can see that the average guess grew closer to the the accurate result after the participant used the VR application.

As you can see in Fig. 8, Questions 9 and 10 both show that the average guess grew less accurate after using the application compared to the calculated result. Question 9 asked "How far would the mass travel if launched at a 45 degree angle on an Carme-sized planet with high atmospheric pressure? (gravity: 0.1 m/s^2, surface pressure: 20 bar)" and had an initial average estimation of 17.74 m. After using the application the average estimation increased to 22.01 m, when the actual value was 1.74 m. It is important to note that estimates after using

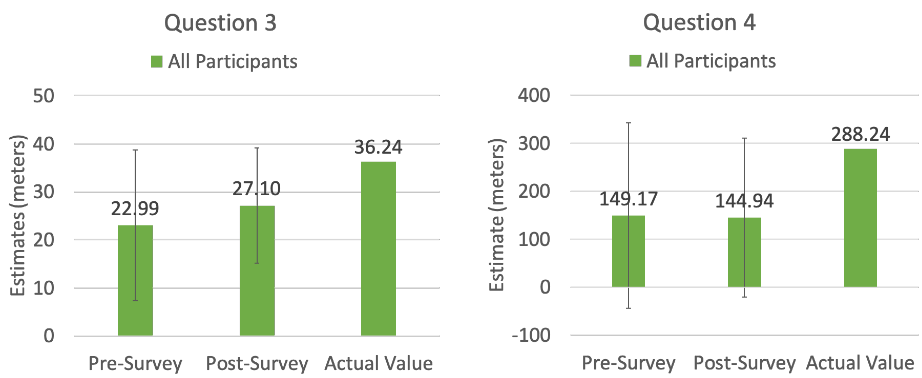

Fig. 5. The Average Bounded Response of Questions 3 and 4.

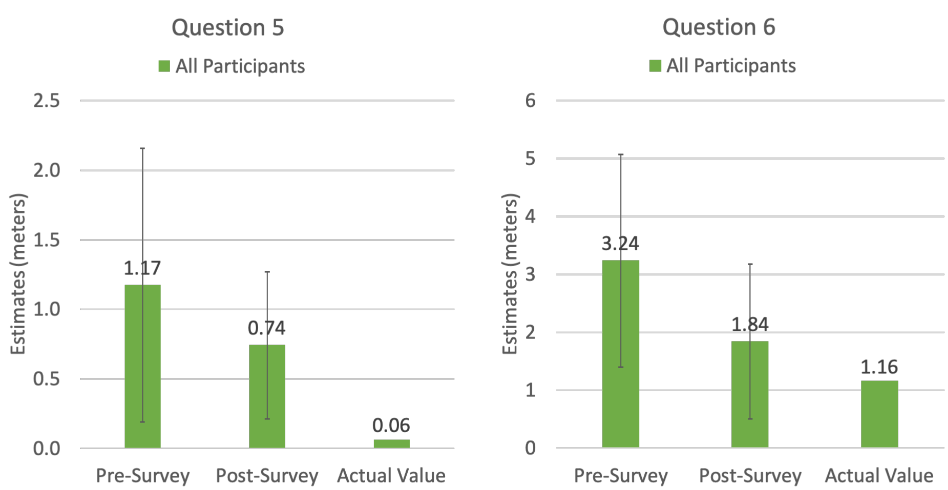

Fig. 6. The Average Bounded Response of Questions 5 and 6.

the application had a standard deviation of 18.78 which indicates a high degree of uncertainty.

Question 10 displays a similarly high standard deviation, but a much lower degree of error. In question 9, average estimation error ranged from 16 m to 20.27 m whereas the average estimation error in question 10 ranged from .42 m to .67 m. When contrasted with Fig. 3 we can see that the major of users actually improved their estimate, but those who did not improve made estimations that were a high order of magnitude away from the actual answer, resulting in an less accurate post application average estimation.

On average, the top third of our participants "showed learning" on 8 questions, while the bottom third (on average) "'showed learning on only 5 questions.

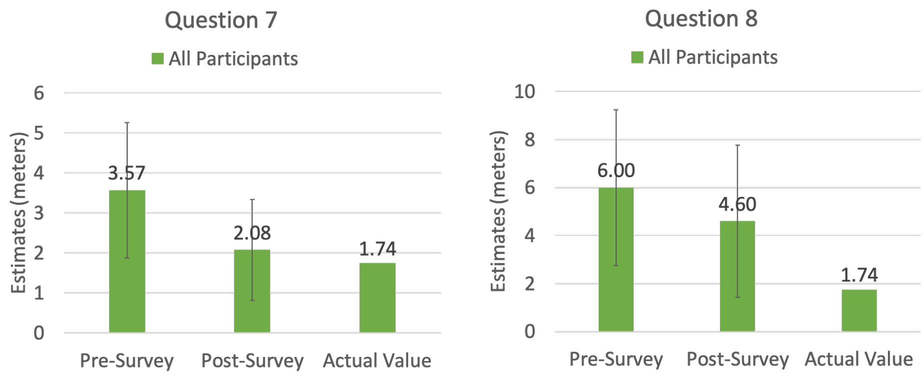

Fig. 7. The Average Bounded Response of Questions 7 and 8.

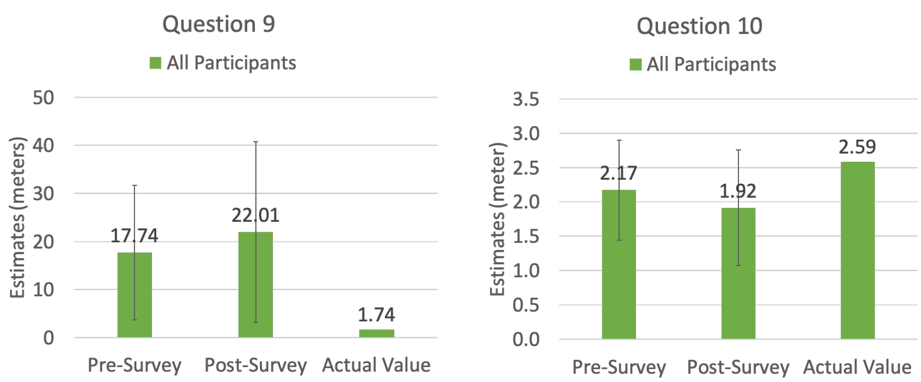

Fig. 8. The Average Bounded Response of Questions 9 and 10. These were the only questions to show (on average) a less accurate estimate after the application.

Surveys were used to evaluate the VLE experience during and after the using the application. Fig. 9 shows the results of both surveys. The surveys collected the users reactions to categories listed in both graphs of Fig. 9 and showed a definite high rate of enjoyment, the general high rate of attention indicators (basic attention, temporal dissociation and transportation) and the surprisingly high emotional involvement. Notably, participants rated the challenge of the VLE greater after experiencing the VLE. This is because their overall perception encompassed the entire experience, including the questionnaires.

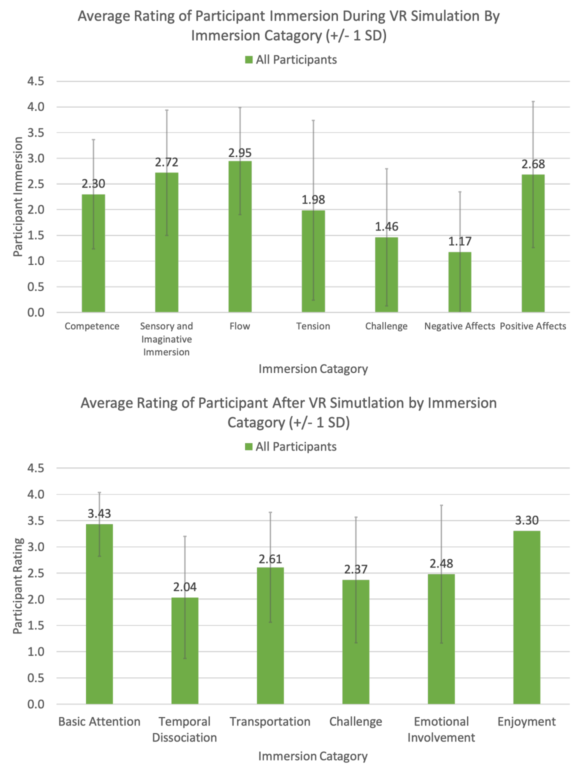

Fig. 9. Immersion Feedback from Participants. (Left) This data is the polling that happened during the application usage. (Right) This data is the polling that happened after using the application.

5 Conclusion

Through our research we have found that a semi-tangible application in virtual reality provides a high level of immersion and enjoyment. In addition, the results from the pre- and post- survey indicate a positive learning outcome for the majority of our participants. This was concluded by data supporting their gained knowledge on the importance of scale and order of magnitude in Newtonian mechanics.

Furthermore, the surveys reveal a high level of user attention due to the VLE's immersive nature. Hence, the first person perspective and kinetic actions required by the VLE create a powerful learning tool for teaching abstract scientific concepts.

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