LEARNING PHYSICS IN THE METAVERSE : EXPLORING THE POTENTIAL OF USER PROGRAMMABLE PHYSICS LAWS IN VR FOR EDUCATION

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1 Introduction

Physics education has long been challenged by the difficulty students face in developing a deep intuition about the underlying principles behind the mathematical formulas they encounter. For many students, these formulas often appear as abstract mathematical structures to be manipulated, lacking a tangible connection to the real-world phenomena they describe. Consequently, students may struggle to grasp the profound implications and practical applications of these formulas.

Various educational tools and simulations have been devised to bridge this gap between formulaic knowledge and real-world understanding. For instance, physics simulations like PhET [2] have been utilized to aid students in visualizing and exploring physical concepts. However, despite their advantages, these simulations often fall short of replicating the authentic experience of reality. This could lead to a limited level of engagement and connection for the students, as they would perceive the simulation as a mere computer program, distinct from the genuine world it aims to represent.

To address these challenges, we propose harnessing the potential of Virtual Reality (VR) as a powerful educational tool for learning physics. VR technology has the unique capability to imbue computational experiences with a remarkable sense of reality, a concept commonly referred to as "presence" [1]. By seamlessly blending virtual simulations with immersive environments, VR can potentially transcend the fidelity gap that students encounter when interacting with traditional simulations. It offers a promising avenue to bridge the divide between mathematical formulas and the tangible behavior of objects in the real world, providing students with an unprecedented opportunity to truly experience the fundamental principles of physics.

To test our hypothesis, we developed a small learning game, with the primary concept being to provide users with the ability to reprogram the laws of physics, and witness the consequences in the virtual world. The game comprises four levels. Two of these levels were dedicated to exploring the concept of projectile motion, while the other two focused on teaching harmonic oscillators. Within each field of study, we experimented with two different approaches. The first approach involved challenging the user to analyze the impact of altering specific parameters on the motion of objects. In the second approach, we provided users with an opportunity to experiment with mathematical formulas and witness their manifestation in the virtual world. The game served as a platform to investigate the potential of utilizing VR for physics education. After completing the initial version of the game, we conducted a user study to assess both its usability and its efficacy as a tool for learning.

In the subsequent sections of this report, we will provide a technical and qualitative description of the game developed. Then, we will outline the user study that was conducted, detailing the methodology employed and the ensuing results obtained from the study, as well as discuss what these results imply.

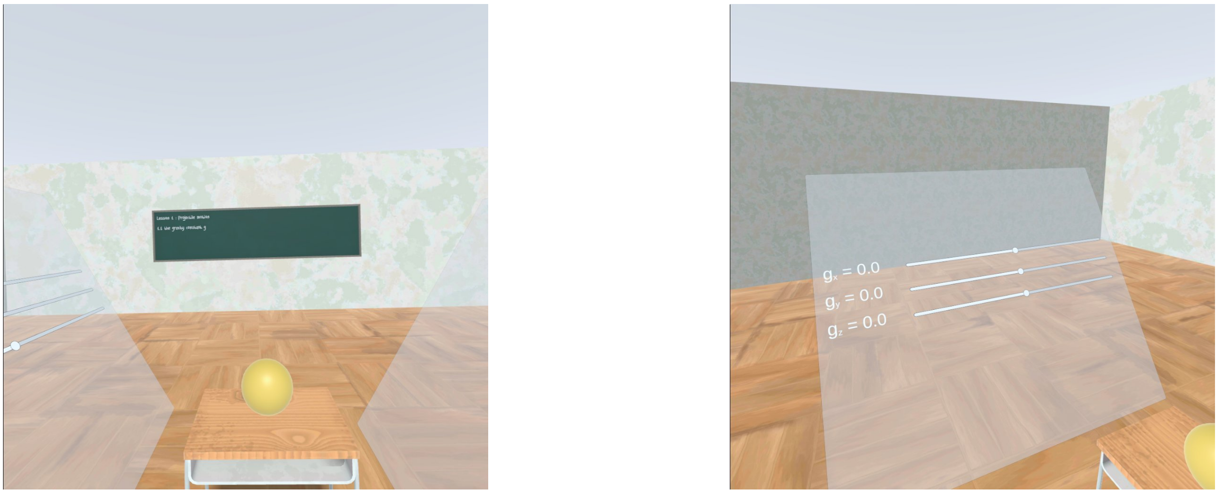


Figure 1: Level 1

2 Material and Methods

2.1 System Design

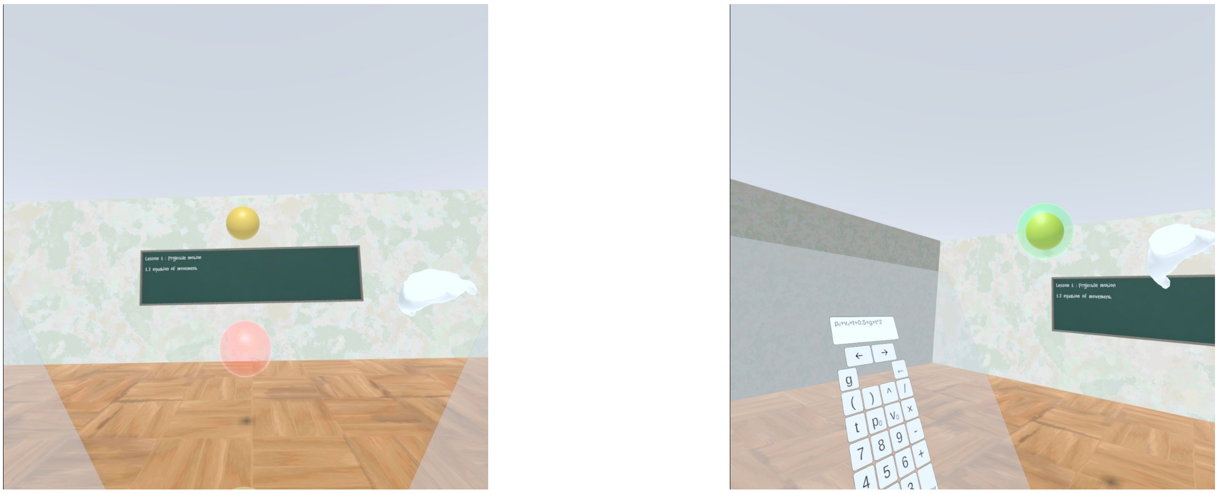
2.1.1 Qualitative Description

The game developed consists of four levels, trying out two different learning methods with two physical concepts. The player can freely move from one level to another even without having "finished" the current one.

Level 1 : The effect of gravity on a thrown object In the first level, the player can grab and throw a yellow ball around. At first the ball will move in a uniform linear motion, that is, in a straight line with constant velocity. This is because all coordinates of the gravity constant are initially set to 0. When throwing the ball, a second red ball appears at the throwing position and follows the path it would follow if the gravity constant was equal to the one on Earth (with the y-coordinate equal to -9.8, and all other coordinates equal to 0).

The goal for the player is to make their ball follow the same path as the red one, by modifying the value of the gravity constant. To do so, they can move three sliders located on a floating canvas next to them, with each slider corresponding to a coordinate. Once they have found the correct value, the two balls will have the same trajectory, and the color of the example ball will turn to green to show that the player managed to solve the level.

Level 2 : Setting the equation of the trajectory of a projectile The second level is similar to the first one, in the sense that the player can throw a yellow ball around that will move in a straight line while a second example ball will appear and fall down as an abject would on Earth.



(a) With an incorrect formula

(b) With the correct formula

Figure 2: Level 2

However instead of having access to three sliders, the player can use a keyboard to directly type the equation of the trajectory of the thrown object, with respect to the initial position, velocity, and the time elapsed since the object was thrown. Initially a formula is already input and visible on the input field above the keyboard, which is $p_0 + v_0 * t$, a formula that corresponds to a uniform linear trajectory. The goal for the player is to modify the formula, see how it affect the movement of the ball when thrown, and try making it correct. Once the solution is found, the example ball will again switch from red to green.

Level 3 : The effect of various constants on the motion of a harmonic oscillator
The third level tackles a different field of Newtonian physics. Instead of having to deal with a projectile subject to gravity, the player will have to study the trajectory of a harmonic oscillator, that is, a movement corresponding to the one of a mass attached to a spring and not subject to any other forces like friction or gravity.

The player will be placed in front of a yellow motionless cube. They will have access to three sliders corresponding to three different constants. One of them controls A, the amplitude of oscillation. The next one modifies k, the force constant, also called stiffness of a spring. The third one controls m, the mass of the cube. The initial value for the mass is 0, which is the reason why the cube doesn't move. Moving the sliders will make the cube move from left to right, according to the values set for the constants. Another red cube appears as well, which is as well moving as a harmonic oscillator, but with set values for A, k and m. The goal of the player is to set the constants such that the yellow cube and the example cube are moving on the same trajectory at the same speed. They have to realize what effects increasing/decreasing a constant has on the motion of the cube to find out which ones need to be changed and how. Once they found values that make the trajectories of both cubes match, the example cube will turn to green.

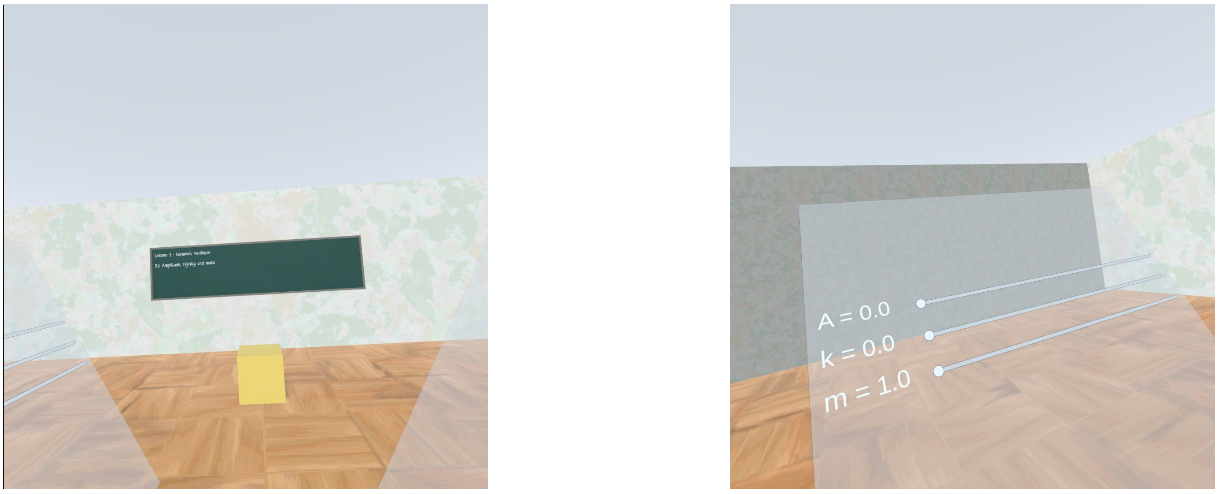
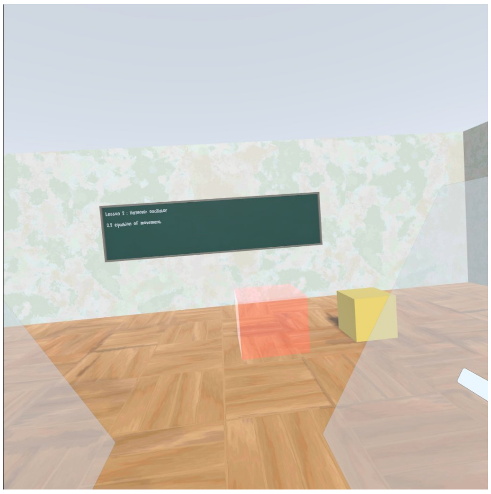


Figure 3: Level 3



(a) With an incorrect formula

(b) With the correct formula

Figure 4: Level 4

Level 4 : Setting the equation of the trajectory of a harmonic oscillator The last level uses the same setting as level 3 but with the approach of level 2, that is, the player has to type the trajectory of a harmonic oscillator, and a cube will move according to the entered formula. The initial formula is equal to 0, meaning the cube doesn't move. The goal is to find $A * sin(\sqrt{k/m} * t)$. The user can make use of what they learned in the previous level about the effect of each constant on the movement of the cube to find the solution.

A deleted level Initially, the first level wasn't supposed to feature a ball that can be thrown. The initial level had the player put in a room with floating objects around them. Setting the value of the gravity constant would make all the objects "fall" according to the value set. The level was supposed to work in coordination with the second one, as the value set for g would be the one g is equal to on the keyboard of the second level. However after designing the harmonic oscillator levels, we realized that it would be better to keep the approach consistent for both physics concepts, both to not confuse the user and to remove an unnecessary variable when measuring learning. Therefore this level was deleted from the version of the game that was tested.

2.1.2 Technical Description

The game was developed in C# using the Unity platform, as well as the XR Interaction Toolkit that provides support for VR. The upside of using this framework instead of another one is that it is platform-agnostic, meaning that it allows the game to be able to run on most VR devices without requiring any additional coding, unlike some other framework like the Oculus Integration that would be only compatible with Oculus devices. However these frameworks have limitations, mainly when it comes to user interface design, meaning new elements had to be created which will be detailled in the following section.

Making an object move according to user-defined rules The initial idea of the game was to have for the user a way to manipulate the law of physics, for example being able to redefine gravity, so that when they throw an object it wouldn't move how it would in real life (that is, falling down) but according to some user-defined behaviour, for example, having an object "fall up" when dropped.

The first step was therefore to have a way to make an object ignore gravity and instead follow a user-defined function. This was done by making the object "kinematic", a feature usually used for making animations, that is, elements that don't move according to the law of physics but to some given behaviour, which is exactly what the objective was. However the object is defined as kinematic only just after being thrown, because kinematic objects don't keep track of their speed, and this is something that is needed when computing the trajectory of a falling object. This also allowed to make use of some usability improvements that the XR Interaction Toolkit provides. For example, it allowed for slight adjustments to the initial trajectory of a thrown object, aligning it more closely with the user's intended motion. This was particularly beneficial for objects thrown at an upward angle, as such actions can often feel cumbersome in VR. By imparting a slight upward impulse to the thrown object, a more responsive and intuitive throwing experience is achieved.

Building a VR keyboard to input formulas The second step was to define how the user would be able to modify the object's behaviour. The idea was to be able to write the equation of the trajectory of the object, however finding the best way to let a user write a formula in VR proved to be quite challenging, as it had to be both natural and easy of use.

$$p(t) = p_0 + v_0 * t + 1/2 * g * t^2$$

The equation of motion of a projectile

Several ideas were considered, and the ideal one seemed to be to let the user access a keyboard in VR, which they can type on using ray emitters from their hands to input a formula. Initially we tried to use the system keyboard functionality of the Oculus Integration framework, however not only was it not a platform-agnostic solution, it was also not easy to use as it provided a keyboard with a full-layout, which was not necessary, as we only needed numbers, operators and some special characters (g for the gravity constant, p_0 for the initial position...). This keyboard was also not easy of use at all, as typing in VR takes longer than using ten fingers. We therefore needed to create a custom keyboard that only contains the necessary characters, since the smaller size would make it easier to use. However the existing frameworks don't allow to define such a keyboard, so it had to be done from scratch. The keyboard was made with buttons placed on a canvas, in a layout mimicking a numeric keypad to make it more intuitive to use.

Parsing and interpreting a written formula Once the user had a way to write an equation, then the formula needs to be parsed in order to be interpreted, that is, to compute the position of the object given the formula. This could have been done using existing parsers, or by simply converting the formula into C# code that would be compiled at runtime. However both these solutions don't allow to provide a comprehensive feedback to the user in the case where the formula entered isn't valid (for example, if it has two + signs in a row, if it starts by a multiplication sign...). The decision was therefore taken to build a parser adapted to our situation.

First, to be able to be interpreted, the formula needs to be converted from an infix expression (expression in which operators are placed between operands) into a postfix expression (expression in which operators follow their operands). This was done using the

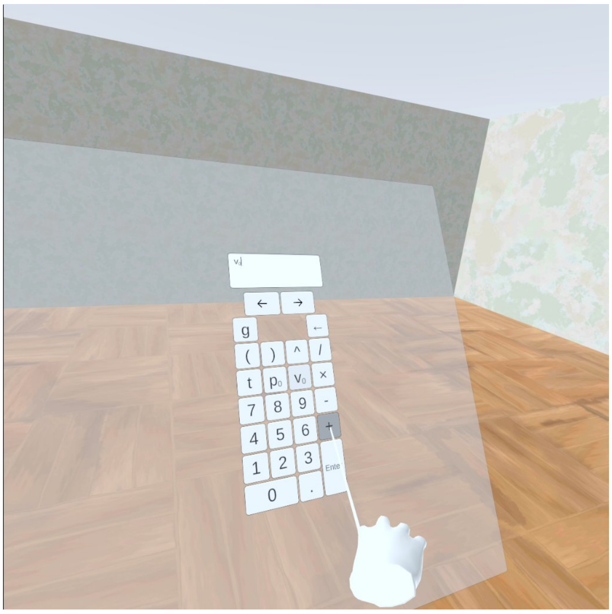


Figure 5: The VR Keyboard

shunting yard algorithm, a method originally developed by Edsger Dijkstra in the 1960s. The algorithm works as follows.
The algorithm employs a stack to process the operators and operands of the expression. It iterates through the input expression from left to right, examining each element. When encountering an operand (such as a number or variable), it is immediately added to the output queue. If an operator is encountered, the algorithm applies a set of rules to determine its precedence and associativity.
Based on the precedence and associativity of the operators, the shunting yard algorithm compares the operator to the ones currently present in the stack. If the current operator has higher precedence or has the same precedence but is left-associative, it is directly added to the stack. However, if the operator has lower precedence or has the same precedence but is right-associative, the algorithm pops operators from the stack and adds them to the output queue until a lower-precedence operator is encountered or the stack becomes empty.
After processing all the elements in the input expression, any remaining operators in the stack are popped and added to the output queue. The resulting postfix expression in the output queue is the equivalent representation of the original infix expression.

$$p_0 \; v_0 \; t \times + \; 1 \; 2 \; / \; \mathrm{g} \; \mathrm{t} \; 2 \; \hat{} \times \times$$

The equation of motion of a projectile, in postfix notation

Once the formula was converted into a postfix notation, it can be easily interpreted.

We go through the expression left to right, and each time we encounter an operand, push it on a stack. If an operator is encountered, the operands are popped, the operation is computed and the result is pushed back onto the operand stack. This process is performed at each update of the position of the moving object to compute its new position.

Performing this allows to give a comprehensive feedback to the user if the formula entered happened to be invalid. It can detect an incorrect parenthesis balancing, misplaced operators, as well as illegal operations such as adding a number and a vector.

Using sliders as another input method We then decided to create an alternative way to let the user define the behaviour of objects. The idea was to allow the user to rewrite the value of the gravity constant g. We first tried using a keyboard, however, since g is a vector, finding an adequate notation proved to be a hard task. Ultimately we realized that in this case using a keyboard wasn't the best way to proceed, and using sliders for each coordinate would be easier to use. The XR Interaction toolkit provides sliders that are interactable in VR so no major functionality had to be built for this.

Improving usability Once the major building blocks of the application were created, some improvements regarding usability had to be done. This was a major concern when developing the application, as playing a game that is not as easy to use as possible is critically detrimental to both the enjoyment and the learning potential of the experience. We'll describe here two notable improvements.

The first improvement was to get rid of any "Reset" button. At first, after having thrown an object with a user-defined behaviour, the user needed to press a button to make a new object appear for them to try again with a new formula. However, this can be cumbersome as it involves an additional action, which in VR isn't insignificant, since it requires positioning the body in the direction of the button, moving the arm towards it and pressing a key on the controller. We therefore considered removing the reset button and making the object respawn automatically, but the question was when, and how it should be implemented. The solution found was to make a new object reappear each time the previous one is thrown. In order to achieve this, the game saves the initial state of the first object, and each time an object is thrown creating a new object in the same initial state. Each object has a lifetime to avoid having too many objects to handle. Each are also updated each time a formula is modified or a cursor is moved.

Another major usability improvement was the addition of a movable cursor to the formula keyboard. Before that the user could only write at the end of the formula, meaning if they wanted to modify it they could only add or delete on top of the original one, but not modify something in the middle of the formula. This could have been tedious for a user to have to modify a single number somewhere in the formula, as all that was written after had to be deleted and written again. The obvious solution was to add a movable cursor to modify the desired part of the text. However this was something challenging to implement, as input fields in Unity don't display a cursor if the element doesn't have focus, a situation that never occurs in the context of VR. The only possible solution was to build a custom cursor, and compute its position according to the number and the size of the characters before it, then allowing the user to move it via arrow buttons.

2.2 Study Design

2.2.1 Participants

We recruited five participants for the user study. Three of them were people experienced with digital learning methods, among which two had learned the physical concepts seen, albeit more than 8 years ago. The last one had no background in physics. The other two participants were students that had learned the concepts seen less than 5 years ago.

2.2.2 Procedure

The study was 30 minutes long. Participants spent the first 20 minutes using the VR app and the final 10 minutes answering questions about their experience. The questions concerned mostly the usability of the application, for example if they had trouble interacting with the keyboard or the sliders, or if they encountered bugs or glitches. We also asked them if the feedback given by the application was clear and as the participant expected it to be when entering a right/wrong formula and interacting with objects. There were also some questions related to the learning potential of such an application in their opinion, as well as if they thought the VR environment was enhancing or detracting from the learning experience. The detailled interview protocol can be found in the appendix 6.

2.2.3 Data collection

We took notes based on our observations and interviews. We also asked the users to give a rate from 1 to 10 to the usability of the application, and computed the average.

2.2.4 Data analysis

We analyzed the notes after conducting our study to better understand the users' experiences with the app, whether it has potential for helping students learn physics, and how it could be improved to attain this objective.

3 User Study Results

3.1 Usability

Overall the participants considered the application to be easy of use. There are still some improvements that need to be done, especially on the keyboard. The main trouble participants had concerned the "Enter" button that needs to be pressed each time the formula is modified. Participants would usually forget to press it and try throwing the ball,

and even if they do press it, there's no feedback telling them the formula was successfully modified (while there is one if the formula is invalid). Getting rid of the Enter button would be an improvement, however this is not so trivial as the validity of the formula is checked at the time the button is pressed, so this is something that should be done at another time without making it too confusing for the user.
Some users also tried multiplying variables without the multiplication sign, for example writing $Asin(t)$, which isn't supported by the parser. However the application tells the user about this when they try writing such an expression so they usually understand and do not try a second time.
The average rating between 1-10 given was 8.4.

3.2 Enjoyment

The participants with previous background in physics enjoyed the experience, especially the second level. They liked the idea of being able to interact with an object whose behaviour they defined themselves. The second part with the harmonic oscillator got a bit less enthusiasm for some participants, as they were not able to interact with the cube itself.
Two of the participants tried entering fun formulas even after competing the level, which shows this was something they enjoyed doing.
However the participant with no background in physics was too confused to enjoy the game, with too many unknown concepts such as axes or the meaning of variables like v_0 and t.

3.3 Impact of VR on the Experience

All participants agreed that for the first two levels, VR had a very positive impact on the experience, because the possibility to interact with the ball was good for immersion. Also a 3D environment is better for a 3D process such as projectile throwing.
However, the oscillator levels felt like they could have been done outside of VR, as they don't involve any interaction and could be done in a 2D setting. Some participants felt like the VR environment was detracting from the experience in the third level, as they often had to move their head back and forth between the cube and the canvas.

3.4 Impact on Understanding of Physics Concepts

For the participant that had no background in physics, the mathematical knowledge required to solve the levels was too advanced, and they couldn't progress without extensive help from the interviewer, therefore the application is inappropriate for such a mathematical level.
All the other participants had seen the formulas before, and considered the game to be a good refresher and a way to rediscover concepts they had forgotten about. They didn't feel like the application helped them better understand physics, but the fact that they were able to solve the levels or get close to a solution without using the usual process

of deriving Newton's law, but instead through observation and trial-and-error shows that the game may help understanding physics formulas from a different perspective.

3.5 Appropriateness for Use in the Classroom

The participants felt like the game could be a good complement to a usual class on Newton's law, as it creates a bridge between the mathematical and physical world. Some suggested that having a collaborative mode would be good, that is, having multiple students in the same VR environment or having an asymmetric setting with one student in the VR world while the others help them from outside.

4 Discussion

The findings from the user study indicate that the developed application may not be well-suited for beginners in physics due to its reliance on mathematical knowledge that they typically lack. This issue of mathematical prerequisites is a common challenge in physics education, as students often encounter mathematical formulas in physics classes that involve concepts they have not yet encountered in their mathematics curriculum. An illustrative example of this challenge is the harmonic oscillator, where the derivation of the associated formula involves solving a differential equation. However, students are typically introduced to the concept of the harmonic oscillator before they learn how to solve differential equations, resulting in difficulties in comprehending the formula. Consequently, students often resort to rote memorization rather than developing a genuine understanding. While the game's approach circumvents the need for knowledge of differential equations, it still requires familiarity with certain mathematical concepts, such as the period of a sine function or the growth of a square root function. Thus, while the game partially addresses the issue of mathematical background requirements, it does not entirely resolve the challenge.

Additionally, the findings indicate that while a VR environment has the potential to enhance the learning experience, the development of such an application in VR presents numerous challenges that need to be addressed to fully leverage its benefits. Despite significant efforts to ensure the application was easy to use, participants in the study raised notable usability concerns, highlighting the complexity of resolving these issues within a VR context. The importance of interactivity was also evident from the study. Participants expressed a greater sense of engagement and found levels that offered opportunities to interact with objects more beneficial compared to those with limited interactivity.

5 Next Steps

In this section, we will outline the potential future directions for our research, considering the insights gained from the study.

Next iteration of the app The subsequent version of the application should prioritize resolving the usability issues identified during user testing. Key enhancements will involve eliminating the need for an Enter button and minimizing the requirement for excessive head movements. Furthermore, it is essential to introduce interactive elements to the harmonic oscillator levels to enhance engagement and comprehension. Expanding beyond Newtonian physics, exploring other fields of physics could also be a valuable avenue for further investigation.
Moreover, to enhance the overall user experience, implementing gamification elements could be a fruitful improvement. For example, a potential approach could involve setting a goal for each level, such as maneuvering a ball through multiple rings, wherein users are required to determine the appropriate formula to accomplish this task. As users successfully navigate through more rings, they would accumulate points, fostering a sense of achievement and motivation.

Next studies Additionally, to further evaluate the effectiveness of the application in terms of learning outcomes, conducting a new user study is recommended. This study would shift the focus from usability to the actual learning capabilities of the app. One potential approach would involve dividing a group of students into two subgroups. Both groups would receive traditional lectures on Newtonian physics, then the first subgroup would utilize a physics simulation on a computer, while the seocnd one would engage with our VR application. Following the learning sessions, all participants would be assessed with a series of questions to measure their learning gains. By comparing the results across both subgroups, we can deduce which method of instruction proved to be the most efficient and effective in facilitating learning. This study would provide valuable insights into the educational benefits of our VR application and enable us to make informed decisions regarding its implementation and further improvements.

6 Conclusion

In summary, our investigation into the potential of using Virtual Reality (VR) for learning physics has shed light on several important aspects. The immersive and interactive nature of VR environments holds great promise for enhancing the learning experience in physics, particularly through features like being able to play around with objects having user-defined behaviors. While this approach may not be ideal for beginners due to the prerequisite knowledge of complex mathematical concepts, it can serve as a valuable tool to develop an intuition about the relationship between formulas and real-world phenomena, complementing traditional lecture-based approaches.

However, when building such an application, extensive attention has to be put into usability, and while Unity and the XR Interaction Toolkit are powerful tools in helping build a VR application, they have limitations that arise when trying to make a user-friendly interface. This is evident in challenges encountered, such as the difficulty of implementing a functional cursor for input fields.

Hence our investigation underscores the potential of VR as a powerful tool for learning physics. With refinements an application like the one developed could be used in classrooms, and further studies should be conducted to assess the quantifiable learning gains achieved through this approach.

References

[1] James J. Cummings Jeremy N. Bailenson. “How Immersive Is Enough? A Meta-Analysis of the Effect of Immersive Technology on User Presence”. In: *Media Psychology* 19.2 (2016), pp. 272–309. DOI: 10.1080/15213269.2015.1015740.

[2] *PhET*. URL: https://phet.colorado.edu/.

Appendix : Interview Protocol

- Explain the purpose of the app (to help students develop better understanding about physics formulas, specifically how the different parts of the formula are related to behavior of objects they describe)
- Have participants work through each of the levels, with help from the interviewer. Using the casting functionality in the Meta Quest Developer Hub to see what the participant is doing.
- Observations to make during the experience:
  - How long does it take them to get comfortable with the interface?
  - What usability issues do they have in each of the levels?
  - Do they understand the objective of each of the levels?
  - Are they able to find the correct solution to each of the levels?
    * Do they get progressively closer to the correct solution?
    * In what ways do they get stuck?
- Questions to ask after the experience:
  - Can you describe your overall experience using the application? How intuitive did you find the application interface?
  - Did you have any difficulties inputting physics formulas? If so, what were they?
  - Did the application respond as expected when you entered a correct formula? Can you provide specific examples?
  - What happened when you entered an incorrect formula? Was the result in line with your expectations?
  - How did the behavior of objects change when you modified the formulas? Was this change clear and understandable?
  - Do you feel that using this application helped you better understand the physics concepts and formulas involved?
  - Was the feedback provided by the application (such as objects behaving incorrectly due to an incorrect formula) helpful in understanding the formulas?
  - Were there any features that you felt were missing or could be improved upon?
  - Did you encounter any technical issues or glitches while using the application?
  - How would you rate the overall usability of the application on a scale of 1-10?
  - Would you recommend this application to students learning physics? Why or why not?
  - How did the virtual reality environment enhance or detract from your learning experience?

- Can you suggest any additional physics concepts or formulas that you would like to see incorporated in the application?
- How did your understanding of the physics concepts change before and after using the application?
- How do you think the application could be used in a classroom setting?
- Did you enjoy the process of learning physics through this application more than traditional methods?
- How could we improve the application to make your learning experience more enjoyable and effective?