Developing Student's Comprehensive Knowledge of Physics Concepts by Using Computational Thinking Activities: Effects of a 6-Week Intervention

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Abstract—Computational thinking has been identified as an important approach for enabling students' better comprehension of STEM concepts as well as scientific procedures. Computation solutions are useful in STEM concepts as they are simplifying mathematical problems so that STEM or physics theories can be applied to problems that have mathematically complicated solutions. Visual Python library provides a 3D environment where learners may design 3D objects, encode physics equations, and study the effects of altering parameters. As the environment created uses simple equations (force or momentum dependent) to compute solutions, students are able to grasp hard mathematical concepts and understand their importance in real-life problems. The implementation and outcomes of a 6-week teacher-led computational thinking intervention with groups of 12th graders (n = 60) are described in this study. Two research questions are being addressed using quantitative analysis and a quasi-experimental approach involving a pre- and post-test. The participants who received the six-week implementation in the experimental group performed significantly better on points covered by simulations compared to the control group, which received only standard teaching lectures. The results indicated a statistically significant difference in mean scores between the experimental group (M = 24.03, SD = 4.68) and the control group (M = 20.3, SD = 5.38). The findings indicate that implementing computational thinking activities not only improves students' knowledge of physics concepts but also improves visual thinking, allowing students to comprehend the problem better cognitively.

Keywords—computational thinking, VPython, FCI, visual thinking, physics

1 Introduction

In today's world, computer technology's applicability to nearly every subject of study has altered the way work is done, and people cannot imagine life without it [1]. Electronic devices, especially information and communication technology, have provided the latest products by developing their functionalities, so they can be utilized to support the learning process in education and other disciplines [2]. Just about anything we utilize in our daily lives is based on computer programming. As a result, familiarity with programming is a pre-requisite for understanding the digital world. Programming allows you to create new things, solve problems, and put your ideas into action [3]. Programming and Computational Thinking (CT) are closely connected, and their bidirectional relationship has been extensively documented in the literature. Programming facilitates the development of CT, whereas CT offers programming with a newly enhanced function [4,5]. In theory, CT does not require programming, but describing a solution to a problem as a program is the ideal method for evaluating that solution. The computer will execute the instructions and provide the student with an opportunity to tweak their solution until it is extremely exact [6]. Thus, CT is not always about programming; rather, it emphasizes problem-solving that fosters learning experiences [7]. The comfort and ease that technology has brought to many parts of daily life can't be disputed, no matter how or where technology has been used [1]. When used properly, technology has the potential to dramatically extend human capacities and alternatives for education, knowledge acquisition, and research [8]. To meet today's challenges of the 21st century, students must learn in an educational setting that encourages collaboration, critical thinking, and analysis both individually and collectively [9]. In some countries, CT has become an important part of education at all levels and a core skill [10].

Croatia considers CT a vital aspect of Informatics. According to the new Croatian curriculum, the emphasis of the educational process in the subject "Informatics" should be on problem solving and programming to assist students acquire computational thinking skills, which facilitates comprehension, analysis, and problem solving. Within the realms of computing, computer science, and informatics, computational thinking is recognized as a crucial concept in the state of Georgia. In Finland, programming is understood to be a technological process or task that is carried out by making use of a digital device and various programming languages. Therefore, programming is simply one component of Computational Thinking/Algorithmic Thinking. It may involve breaking a problem down into its component parts, recognizing and executing patterns or formulas, programming, or automating tasks. Coding and algorithmic thinking are crucial aspects of CT in Serbia. Coding is the use of a programming language to solve a problem through the use of a computer. In Slovenia, CT is viewed as "the cognitive processes involved in formulating a problem and communicating its solution in such a way that it can be easily and efficiently implemented by a computer." Notably, the Slovenian definition continues by embracing a broader, more transversal dimension, stating that computational thinking is applicable to different professional and scientific disciplines, leads to the growth of metacognitive skills, and promotes cognitive and creative problem solving [11].

This study focuses on how computational modeling influences 12th grade students' understanding of physics concepts by means of Visual Python. Students are able to create 3D environments where physics principles can be applied using mathematical expressions and parametrize the variables. Being able to change the variables enables learners to visualize, understand, analyze, and explain how a system's behavior changes under specific circumstances.

1.1 Computational thinking

Everyone is affected by computational thinking, regardless of their career field. It's crucial to note that computing is driven by three factors: the scientific community, technological advancements, and society [12]. Henderson et al. [13] and Wing [12], refer to the term "Computational Thinking" as an ubiquitous metaphor for reasoning that leverages the strength and boundaries of computing processes, whether human or machine-based. CT necessitates analytical and problem-solving abilities, as well as mindsets and habits rooted in computer science but inherently practical [14]. It has the potential to serve as a comprehensive framework for capturing the underlying essence of computers and communicating it in an understandable manner to students and the public [13].

Computational thinking involves the following problem-solving steps:

- Designing problems in such a way that they can be solved with the assistance of a computer as well as other instruments
- Data organization and analysis
- Modeling and simulating data
- Using algorithmic thinking to automate solutions
- Finding, assessing, and improving the efficiency and effectiveness of a process by putting into practice potential solutions
- Generating a generic solution that may be applied to a wide range of challenges

There are a number of character traits or attitudes that go hand in hand with CT and help to reinforce and improve these abilities:

- Comfort with complexity
- Perseverance in solving challenging issues
- Acceptance of ambiguity
- Adaptability to uncertain situations
- Communication and teamwork skills to accomplish the same objectives [4]

Computational approaches and models enable us to solve problems and develop techniques that we would not be able to solve on our own [12]. Connecting CT problem solving to real-world scientific, and humanities challenges is essential. This means students can put their knowledge and abilities to use in real-world contexts [14]. Furthermore, creativity serves as a crucial instrument that enables pupils to implement their new ideas and expand their creative skills through innovation. In recent years, computational thinking has become increasingly popular. In pre-school, for instance, ScratchJr has been used to teach coding and other skills coherently to young children [15]; in mathematics, Verawati et al. [16] have developed an android-based learning platform to improve problem-solving skills.

Code geniuses aren't enough anymore; students need to know how to recognize unique challenges, efficiently communicate, find solutions, and think creatively to succeed [17]. Learners must first construct a conceptual framework of the phenomena, identifying all essential factors and their relationships. They must then transfer these concepts into a computer simulation by employing exact terminology and syntax.

They can iterate their model until it is a reasonable representation by observing the simulation results. Abstraction and programming are core principles in computational thinking [18].

1.2 Why Visual Python?

Computational physics provides the opportunity for physics educators to investigate complex, non-idealized systems that are out of reach for standard analytical approaches [19]. For various reasons, demonstration of physical and computer experiments is critical to the learning process. Today's student activities are heavily influenced by computing, and many fields of study are related or directed by computing [20]. To begin, a visual experiment enables us to compare theoretical knowledge to the world's physical representation. Secondly, computer modeling enables a more in-depth examination of physical phenomena. Thirdly, developing a physical and computer demonstration enables you to acquire a better qualitative understanding of the content, as writing your own program to represent a physical process is impossible without first conducting an in-depth examination of the phenomenon being examined [21]. As a result, computational physics requires critical and innovative thinking [20]. Setting up codes to precisely imitate a real system is typically a difficult undertaking. Designing and testing a program to simulate a physical phenomenon inevitably entails times of confusion or difficulty [20]. Because of its remarkable ease-of-use for interactive 3D graphics, no prior programming knowledge is required to develop programs that feature real-time 3D visuals in VPython for physics students. VPython is a Python module for visualizing scientific data in three dimensions [22].

VPython is a Python 3D graphics library that enables programmers to access a navigable 3D display. By importing graphics libraries into a virtual 3D window or visual scene, students can generate simulations quickly and easily. The default properties of these 3D objects can be changed by students, giving them complete control over their visual appearance [19]. Python is widely used in education. For example, Lazarinis et al. [23] conducted a study aimed at enhancing pre-service and in-service teachers' coding skills, in which teachers learned to code and were required to confront problems in a series of ordered steps that demanded them to analyze and organize data in structures. According to Zourmpakis et al. [24] teachers can exert considerable effect on the gamification of science education.

By using VPython programming, students can strengthen their computational and programming skills by using differential equations from the mathematical model. By emphasizing the mathematical-physical model relationship, students gain a more in-depth understanding of the physical phenomena under investigation [25]. VPython is widely used in physics and mathematics, particularly when working with three-dimensional objects such as vectors, geometric forms, and projectile motion [26, 27].

1.3 Research questions

When it comes to science education, computational thinking is a critical skill that is rarely integrated into instruction in a realistic way. According to a number of studies, the building of models of physical events has been highlighted as a critical strategy for assisting students in gaining a better understanding of both science concepts and scientific processes. These assertions form the basis of our two research questions:

RQ1: Is computational thinking beneficial for students' comprehension of physics concepts?
RQ2: How does computational thinking support students in developing a more comprehensive knowledge of physics and science concepts?

2 Methodology

2.1 Design

The study was designed in a quasi-experimental approach and included a pre- and post-test utilizing the FCI (Force Concept Inventory) as a measure of effectiveness. Four high school classes taught by the same physics teacher were divided into two groups: experimental and control. At the start of the semester, both experimental and control groups received a hybrid pre-test of the FCI inventory consisting of 30 questions. For six weeks, the experimental group received an intervention consisting of teacher-led computational thinking activities, whereas the control group received traditional teaching instructions. After the 6-week computational thinking intervention, both groups took the same FCI inventory post-test. This was done to see if the experimental group's overall understanding of physics had improved as a result of the intervention.

2.2 Participants

A total of 60 students from the twelfth-grade were enrolled in the study at a public high school in Albania. 30 students from the experimental classrooms (M_{age} = 17.4 years, SD = .48, 53.3% girls) and 30 students from the control classrooms (M_{age} = 17.2 years, SD = .54, 40% girls). Participants were chosen based on non-random criteria and an accurate description of the study, and their oral consent was obtained before they were allowed to participate.

2.3 Pre- and post-testing procedures

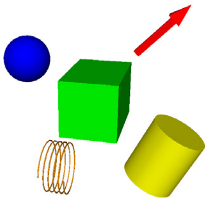
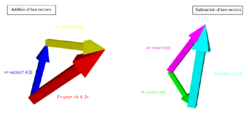
The Force Concept Inventory (FCI), developed in 1992 by Hestenes et al. [28], was used as a pre- and post-test. The FCI consists of 30 multiple-choice questions (MCQs) with five possible answers, and it assesses students' understanding of velocity, acceleration, and force. In the test items, there are numerous distracters that represent commonplace assumptions about the nature of force and its effect on motion. The test's vocabulary is primarily made up of everyday words and phrases, and the problem setups contain objects such as cars accelerating, elevators moving, or boxes being pushed. Thus, students can understand the problem setups in it even if they have not yet taken a lecture on physics. The reason for using this concept inventory as a pre- and post-test is that many students struggle to understand fundamental physics concepts such as force and how gravity impacts objects. As a result, the activities implemented in the experimental group address these misconceptions directly, as students are able to modify various factors such as velocity, gravity, force, and so on and observe the effect on the system.

In advance of the first physics lecture, both the experimental and control groups completed a pre-test. For six weeks, the experimental group participated in VPython activities in conjunction with the lecture explanation, while the control group continued to take the lecture as usual. Following the 6-week implementation period, a post-test was undertaken to determine whether the experimental group's implementation was beneficial or not, in contrast to the control group.

2.4 Description of the interventional activities

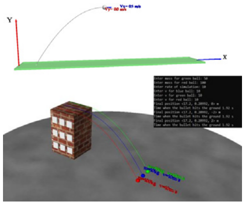
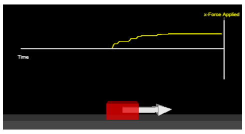
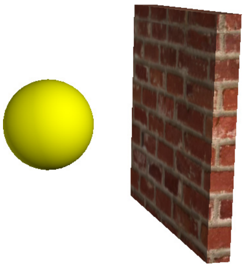
An intervention consisting of teacher-led computational thinking activities delivered using an open-source programming environment known as VPython was provided to the experimental group over the course of six weeks. Each week, students were presented with an activity that was based on the teacher's existing physics curriculum. Throughout the six-week intervention, the teacher spent approximately 6.33 hours with students practicing in-class activities. In this regard, it is essential to emphasize that the experimental intervention did not take place in addition to the current physics curriculum but rather as an integral part of it. To put it another way, teachers were not required to devote additional time to the teaching of these activities. Instead, teachers were requested to perform the VPython activities in place of the time that would have otherwise been spent on regular physics instruction in the classroom. The names of the activities, as well as their descriptions and objectives, are listed in Table 1.

Table 1. A summary of the activities implemented in the experimental classrooms

Name of the Activity	Description of the Activity	Objectives
Activity 1: Introduction to VPython, dealing with 3D objects. 	Discovering the open-source VPython environment, as well as how to install and begin using it. Getting started with creating various 3D objects in different dimensions and colors by specifying the desired x, y, and z coordinates.	Discovering a new 3D simulation environment. Understanding the 3D environment. Seeing 3D objects in various locations and seeing them from various perspectives.
Activity 2: Addition and Subtraction using 3D vectors. 	Employing arrows to generate various 3D vectors and execute addition and subtraction of these vectors, producing a 3D visual result.	Create 3D arrows and work on vectors. Writing a VPython program that performs algebraic calculations of vectors.

(Continued)

Table 1. A summary of the activities implemented in the experimental classrooms *(Continued)*

Name of the Activity	Description of the Activity	Objectives
Activity 3: Interactions and Motion. 	Changing the attributes of elements such as velocity and mass, as well as interacting two or more objects with one other.	Specifying the velocity of a produced 3D object using physics formulas and principles.
Activity 4: Projectile motion 	Creating a 3D projectile motion environment that can be launched in numerous circumstances (without and with height) and adjusting characteristics such as angle, velocity, and mass.	Understanding the fundamentals of projectile motion and watching what happens when certain parameters are altered.
Activity 5: Friction 	Making a 3D prototype with multiple surfaces that can be changed to test how friction varies. Different forces are applied to objects of various masses to understand the relationship between mass and friction.	Recognizing the concepts of friction forces and the significance of applied force in objects of varying masses.
Activity 6: Momentum Principles 	The laws of momentum are used to study what happens when a ball hits a wall in a simulation built from a book exercise.	Discovering momentum concepts through the construction of a simulation based on a textbook exercise and the manipulation of various parameters to observe the type of collision.

3 Results

3.1 Data analysis

In order to compare the results of the control and experimental groups, two independent t-tests were performed in both the first and second periods. The first period refers to the pre-test examination taken prior to the first physics class, and the second period follows the 6-week intervention period. The second research question compares the post-test findings of the experimental and control groups. This comparison evaluates each student's response, with a special emphasis on those problems that require students to utilize their visual imagination to solve and predict the results. Data from the students' comparable pre- and post-test outcomes are shown in Table 2 to provide a summary of the findings.

Table 2. Data from pre- and post-tests between the two groups in the study

	Group	Mean ± SD	SE	t	p
Pre-test	Control	21.73 ± 5.27	0.96	0.85544	0.19791
	Experimental	20.6 ± 4.98	0.91		
Post-test	Control	20.3 ± 5.38	0.98	–2.86502	0.00289
	Experimental	24.03 ± 4.68	0.85		

Notes: *p < 0.05. SD: Standard deviation, SE: Standard error.

RQ1: Is computational thinking beneficial for students' comprehension of physics concepts?

The t-test, with an initial alpha value of .05, was utilized in this research to analyze both the experimental and control groups' performance on the pre-test. We used an independent-means t-test design because one treatment was completed by the experimental group (6-week implementation of computational thinking activities) and the other condition was performed by the control group (standard lecture). The first period's data indicated that there were no straightforward discrepancies in pre-test scores between the experimental and control groups. Even though students in the control group (M = 21.73, SD = 5.27) fared somewhat better than students in the experimental group (M = 20.6, SD = 4.98) during the pre-test, when the t-test is conducted, the result is not statistically significant at p < .05. The second period investigated both groups' post-test outcomes following the 6-week intervention for the experiential group using an independent-means t-test design. The t-test with an initial alpha value of .05 was used to compare the post-test performance of the experimental and control groups. The 30 participants who received the six-week implementation in the experimental group performed significantly better on the post-test than the control group, which received only standard teaching lectures. The results indicated a statistically significant difference in mean scores between the experimental group (M = 24.03, SD = 4.68) and the control group (M = 20.3, SD = 5.38), t(60) = –2.86, p = .0028. The post-test results of students in the experimental group improved significantly after six weeks of implementing computational thinking activities, according to the findings. The findings' comparative results are depicted in Figure 1.

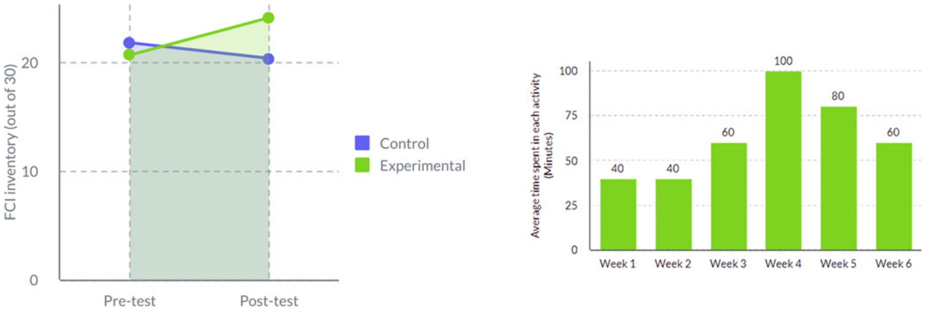


Fig. 1. The results of the pre- and post-tests for both groups, as well as the average amount of time spent on each activity

RQ2: How does computational thinking support students in developing a more comprehensive knowledge of physics and science concepts?

According to the findings of the first research question, we discovered that implementing computational thinking activities for six weeks has a significant effect on students' performance when pre and post tests are compared. However, how does such implementation affect the performance of students? To determine the answer to this question, we carefully evaluated each student's response in the experimental group for the pre- and post-test on each question, with an emphasis on those that needed students to use their imagination to comprehend the problem's circumstances. Our fundamental hypothesis is that computational thinking improves students' visual thinking skills, allowing them to comprehend the proposed context of the problem and have a better understanding of it more easily. As a result, students gain a more comprehensive understanding and are less likely to fall prey to various misconceptions that may arise. The dependent-means t-test with an initial alpha value of .05 will be performed to see if there are differences between the pre and post tests for the experimental group. Table 3 shows the results of the dependent t-test.

Table 3. Pre- and post-test results for 17 questions related to visual skills

	Group	Diff. Mean ± SD	SE	t	p
Pre-test	Experimental	3.06 ± 5.64	1.41	2.16902	0.04549
Post-test					

Notes: *p < 0.05. SD: Standard deviation, SE: Standard error.

In the dependent t-test, just 17 elements from the FCI inventory are analyzed, all of which have a direct impact on the students' ability to visualize the situation of the problem. It was necessary for students to imagine the situation in which the problem happened in order to come up with a correct solution to these problems. Figure 2 shows the results for each question for the pre- and post-test.

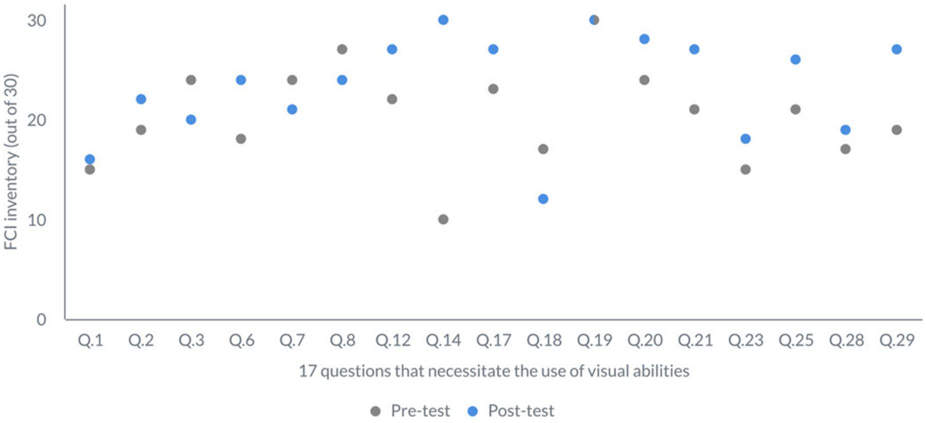


Fig. 2. The pre- and post-test results for 17 questions requiring students to mentally visualize the situation of the problem

Pre- and post-test scores for the experimental group showed a statistically significant difference (Diff. M = 3.06, SD = 5.64), t(17) = 2.16902, p = .04549. The result is significant at $p < .05$.

As shown in Figure 2, four questions on the pre-test, Q.3, Q.7, Q.8, and Q.18, showed better results than on the post-test. To comprehend the causes of these changes, we have thoroughly examined each of the following questions:

- The intervention simulation enables students to comprehend how mass affects projectile velocity, whereas question 3 inquiries about the effect of gravitational acceleration.
- In Q.7 and Q.18, the law of inertia is applied; however, these laws are not explicitly illustrated in our simulations; as a result, there was a small difference between the pre- and post-test results. However, the bulk of Q.7 responses fall between option A (23.33%) and option B (70%), indicating that students can visualize the problem situation but make inaccuracies due to a lack of understanding of centrifugal forces.
- Q.8 refers to collision happening along 2D, while the simulation developed with students shows collision happening between two objects along 1D.

This may explain why the pre-test results were marginally higher than the post-intervention results, as anticipated by the researchers.

4 Discussion

4.1 A summary of the important findings

A six-week teacher-led intervention focused on increasing students' understanding of physics concepts through computational thinking activities was evaluated in this study. When compared to a control group, students who received the computational thinking intervention performed better, improved their visual thinking, and gained a better understanding of the situation.

4.2 On improving physics concepts

The first research question examined whether computational thinking helps students' comprehension of fundamental physics concepts. In this study, we employed the VPython programming environment because simulations can aid in the promotion of CT by allowing users to adjust parameters and evaluate their predicted outcomes. Our findings contribute to a growing body of research indicating that computational thinking encourages students to investigate novel solutions, participate in more direct sense-making, and test a variety of model-based predictions [29–34]. Furthermore, students who participated in computational simulations in class performed significantly better than other students who participated in traditional instruction without the use of simulations.

This study contributes significantly to the use of simulations in physics classrooms, and more precisely, to approaches to computational thinking. On the other hand, this intervention was brief (6 weeks), involved creative experience with a broad range of physics principles (with a heavy emphasis on physics phenomena and misconceptions), and was conducted by the classroom teacher as part of regular physics instruction.

According to Prosperetti and Tryggvason [35], computational physics is critical as a means of learning and comprehending fundamental physics as well as a guide for further in-depth inquiries. In terms of developing ideas for dealing with physics formulas [36], CT has significant advantages for teachers – for instance, from quantum scale simulations of transport processes [37] to understanding vector fields as key components of an electrodynamics course [38] to electromotive forces in a generator [39] and physics laboratory [40]. Regarding the competency levels of educators, Zhang et al. [41] identified a lack of programming and CT knowledge as the reasons why teachers do not incorporate CT viewpoints into their activities. Consequently, there is an obvious need to expand teachers' limited knowledge of technology and strengthen their understanding of its essential concepts and pedagogies.

4.3 On improving student's visual thinking

The second research question of the investigation was to observe how much computational thinking aids in the development of physics knowledge among students. Results indicated that students in the experimental group had significantly improved visual thinking following the intervention and were able to perceive and comprehend the problem situation considerably more easily than students in the control group. Our findings support previous research [42–45] that suggests using simulations can assist science students in developing visual thinking skills such as observation, measurement, prediction, and interpretation of outcomes.

Previous research has linked spatial ability to student achievement in scientific classes. According to Fulmer [46], the visual-spatial abilities of learners need to be improved in order to assist students to better visualize abstract events, get a deeper understanding of them, and improve their overall academic performance. Taslibeyaz et al. [47] indicates that in research concentrating on computer use, CT definitions emphasize programming skills, whereas in other contexts, thinking skills are emphasized more. Several research studies [48–51] identified CT-related thought processes as creative issue solving, problem solution transfer, logical reasoning, data representation, and systemic thinking.

Furthermore, the results confirmed the benefits of computer simulations by promoting interactivity in the physics classroom [52], improving students' performance when learning physics [53], and providing students with the opportunity to explore a broad range of physics topic areas via the multiple representation feature [45,54,55].

5 Limitations

It is worth noting that the study design has some drawbacks. To begin with, classes were not assigned randomly to experimental or control settings. Thus, it is difficult to rule out the possibility that systematic distinctions at the start of the study influenced the study's outcomes. Both groups appeared to be well-matched; indeed, on the pretest, the control group outperformed the experimental group. Additionally, the intervention was brief (6-weeks) and was carried out by the classroom teacher as part of routine physics instruction, which leaves the teacher with less time to complete the task or respond to each student's inquiry individually. Another constraint, ironically, is perhaps the lack of access to technology. It is critical that each student performs the activity independently on his or her own computer during the simulations, and the school should be able to provide computers for each student in the class.

Finally, this study could be enhanced by adding a diverse sample of participants and a range of teachers, as well as by obtaining data from the teacher side.

6 Conclusions

Overall, the findings of this study imply that integrating computational simulations into the physics curriculum has numerous beneficial outcomes. The intervention was carried out as part of the regular physics curriculum, and the teacher worked toward simulations at the start of the school year. The central focus of the intervention was to acquire thorough data on the impact of incorporating computational thinking tasks into standard classroom instruction. Throughout the six activities, students were required to visualize and anticipate specific outcomes, as well as to alter various system characteristics and evaluate the resulting changes. Student-centered learning methods like active learning encourage students to actively participate in their education rather than simply sit back and take notes in class. Students engage in a wide range of activities that include discussion, reading, higher-level reasoning, and more [56]. Additionally, students were exposed to this form of dynamic engagement. For instance, students were asked to create additional activities and modify the offered activities depending on their observations by varying the characteristics, objectives, and environment. Students demonstrated significant levels of engagement with these types of activities, but our findings also indicate that participation in such activities improves students' understanding of a number of significant physics misconceptions. Moreover, it appeared as though the intervention benefited students' visual thinking, a critical core skill for problem-solving. As stated by Verawati et al. [57], we do believe that knowledge can only be retained, comprehended, and actively applied if students are given opportunities to think about and apply what they are learning. In summary, this research demonstrates the potential importance of adding computational thinking into physics teaching practices on a regular basis.

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