Creating a Physics and Computational Thinking Curriculum using a 3D Virtual Learning Environment

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BRIEF. A curriculum taught through a 3D virtual learning environment was designed to help high school students learn and improve their self-efficacy in physics while developing their computational thinking skills.

ABSTRACT. In the light of studies indicating the ineffectiveness of conventional physics courses, physics curricula and teaching tools that embrace aspects of constructivist learning theories are being developed. However, only a few incorporate computational thinking (CT), a computer-science-based problem-solving method, into physics education. This prompted the exploration of the impact of a physics and CT curriculum implemented in a 3D virtual learning environment (3D-VLE) on learning and self-efficacy of high school students. In this case study, four high school students participated in a week-long extracurricular club covering three physics lessons based on learning by modeling. Students constructed knowledge through physics problems on paper in combination with building models in a 3D-VLE. Analysis of pre- and post-tests shows three students increased or maintained their scores in physics and two for CT. Similarly, self-efficacy scores for physics increased for three students and for one student in CT. Despite the students' neutral to positive attitudes towards the club, most students still preferred the lessons of their traditional physics classes. Considering the low sample size and technical issues experienced, these results hint at promising learning outcomes and revisions to the curriculum that can improve the students' learning and self-efficacy in physics and CT.

INTRODUCTION.

The traditional theory of learning, where the teachers use lectures to pass down knowledge to students who are the recipients, has been shown to be ineffective [1]. Traditional physics courses are unable to change the commonsense beliefs that students develop through everyday observations regarding forces and motion of objects [2, 3], which do not align with the fundamental physics concepts. This prevents students from comprehending class material. As a result, students can become frustrated with the class and eventually dislike it [2, 3]. However, school curricula have shifted from the traditional theory to constructivist theories, which advocate for student-centered environments in which students build knowledge through interactions with objects around them [1, 4]. Under this paradigm, teachers become supporters of learning rather than the source of the information students need to learn.

This shift has driven the development of curricula and teaching tools that embrace aspects of the constructivism theory in classes. For instance, noticing the low attendance and failure rate of traditional mechanics and electromagnetic courses at MIT, Dori, et al. developed the Technology-Enabled Active Learning (TEAL) teaching format for those courses [5]. TEAL aimed at helping students develop a better conceptual understanding through visualization, collaboration, and hands-on active learning in specially designed classrooms. While the TEAL format resulted in significantly greater learning gains than traditional lecturing styles [5], many institutions lack resources necessary for implementing the TEAL curriculum [6]. Therefore, J. Pirker, et al. developed Virtual TEAL World (VTW), a flexible, competitive, and economic virtual reconstruction of the physical TEAL environment [6].

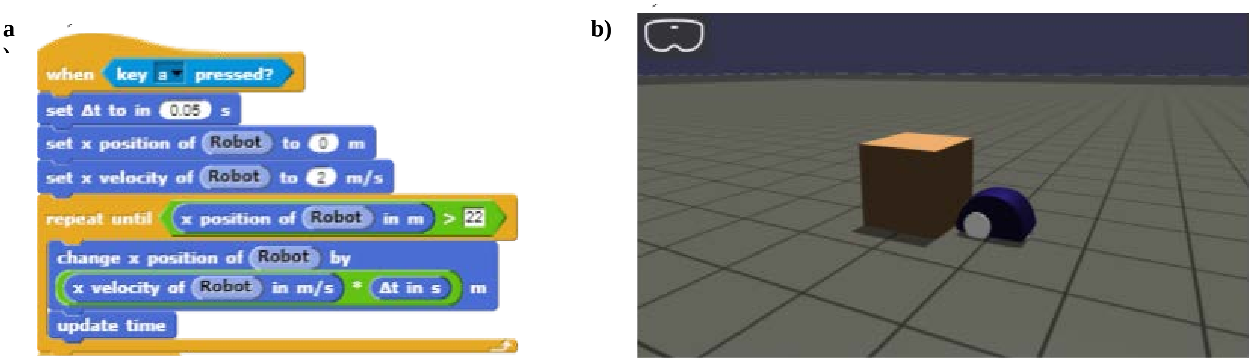
Stil~~l~~, VTW does not provide students the opportunity to develop their computational thinking (CT) skills, which has now become an important component of STEM domains. CT is a problem-solving method where solutions to problems are formulated in forms that can be done effectively by a human or computer using tools and techniques from computer science [7]. While often associated with computer programming and computer science, CT has been used across multiple STEM fields as it is the thinking behind solving complex problems [8, 9]. With computers being an essential part of our world, an understanding of CT provides students with a "digital" perspective that broadens their understanding of our 21st Century world. This understanding of the world, in turn, serves as the basis for students to change our world for the better. In physics, specifically, CT would allow students to build computational models of real-life phenomena to improve their own understanding or that of an entire physics sub-branch.

Collaborative, Computational STEM (C2STEM), developed by Hutchins et al. is one of the few studies that builds on the learning limitations found in VTW. C2STEM is an open-ended learning environment that combines hands-on visual programming and two-dimensional (2D) modeling to promote the learning of physics and CT [10, 11]. Where C2STEM builds upon VTW's limitations, it suffers from a limitation not encountered by VTW: the real-world scenarios that can be modeled utilizing 2D simulations. Three-dimensional learning environments (3D-VLEs), such as VTW, are computer programs that provide three-dimensional spatial visual information, interactivity with the displayed data, and often supplement the visual information with other stimuli (e.g. auditory and haptic) [12]. 3D-VLEs have characteristics such as high representational fidelity [12, 13], the combination of realistic display of the environment and behavior with multidimensional feedback, providing a high sense of presence, giving students greater levels of satisfaction and better learning gains [12, 14, 15, 16]. They also enable more exploration, experimentation, and perspectives, serving as more adequate platforms for applying the constructivist theories [12, 14, 16].

In this case study, we explore the following question: how does a physics and CT curriculum implemented in a 3D-VLE impact student learning and self-efficacy? The hope is that the results of this study will indicate the curriculum's effectiveness at teaching high school students physics concepts while developing their CT skills. Additionally, it would also suggest an increase in the student's confidence with physics concepts and CT, skills as well as positive attitudes towards the lessons.

METHODS.

The environment used in this study was based on the 3D-VLE developed for RoboScape Online [17], that consisted of two parts: NetsBlox and the 3D simulation. NetsBlox is a web-based block-based programming environment [17, 18], similar to MIT's Scratch. The highly visual nature of NetsBlox and its easy to learn syntax enables for a greater focus on CT [17, 18, 19, 20], ideal for the purpose of this study. Within the NetsBlox web-page, the 3D simulation appeared as a draggable window (Figure 1b) that automatically updated to show



```
when key a pressed?
set Δt to in 0.05 s
set x position of Robot to 0 m
set x velocity of Robot to 2 m/s
repeat until x position of Robot in m > 22
  change x position of Robot by
  x velocity of Robot in m/s * Δt in s m
  update time
```

Figure 1. Aspects of 3D-VLE. (a) Script modeling the robot traveling at 2 meters/seconds along the x-dimension until its position is greater than 22 meters. The Δt (“delta t”) refers to the rate of change of time. A larger Δt value results in an increase in the speed at which the simulation runs. (b) Model of the virtual robot position in front of the box view through the window created within the 3D-VLE.

the programmed movement the students built, allowing students to test their program in real time [17].

Although based on RoboScape Online, the 3D-VLE used in this study had a few adaptations made to better suit the purpose of the study. First, a reduction in the number of objects modeled and simplification of the setting to prevent distractions from irrelevant objects and confusion caused from the increased complexity of 3D-VLEs (Figure 1b)[13]. These changes reduce the graphic load and improve the performance of the Chromebooks the students were supplied by the school and used to run the 3D-VLE. In addition to the regular NetsBlox command blocks, physics-specific blocks were added (Figure 1a) to allow students to learn and practice using physics terms while programming in the 3D-VLE. Lastly, the physics of the 3D-VLE were modified to allow for the switch from adaptive movement of objects in the simulation through key presses to movement through position formulas translated into blocks within NetsBlox.

The curriculum developed for this study was taught as part of a high school after-school club in the Metro Nashville Public Schools district across three one-hour sessions over one week. All work students completed was during those sessions, with no homework being assigned. Of the initial ten club members, six successfully completed the permission forms prior to the start of the study and were considered in the data analysis. Subsequently, two of the six students were excluded due to not completing the post-test and the post-self-efficacy survey. Of the students included for the data analysis, 75% of them were in 12th grade and 25% of them were in 11th grade. Of those same students, 50% were currently enrolled or had previously completed a physics course, with the 100% of them completing the standard level class. 75% of them are currently enrolled or had previously completed a programming or computer science class, with all 100% taking it at the Advanced Placement level.

Each lesson was based on the constructivism theory and divided into two 30-minute phases (Figure 2b). The first phase consisted of completing problems on paper that would enable students to grasp the lesson’s concepts. This phase was incorporated to ease the use of the 3D-VLE, especially for students with little to no experience with 3D-VLE or programming. In the second phase, the students applied their knowledge from the previous phase in the 3D-VLE by programming the movement of an object. For either phase, students were not given instructions as to how to solve the problems, requiring them to discover the concept with the material provided, such as formulas and a coordinate plane. However, they were provided limited clues or video clips of the completed programming practice to direct them to correctly solve the problems.

Prior to the club’s start, students attended a session introducing them to the 3D-VLE to provide familiarity with using the blocks and viewing the 3D simulation. Then, for the week that the after-school club was operational, sessions covered three different lessons regarding one dimensional motion (Figure 2a). In addition to learning about physics concepts, the students had the opportunity to develop their CT skills, which included problem decomposition, abstraction, and debugging skills. As providing contexts to 3D-VLEs appear to indicate higher engagement [12, 14, 17], the students were told to imagine themselves as Apple employees tasked with programming an assistant robot throughout these lessons. This narrative was also intended to help students understand real-life value associated with physics and CT by beginning to envision how their actions would be useful in the future.

To evaluate the effectiveness of this curriculum, the students completed a comprehension questionnaire, administered as pre-test and post-test. The questionnaire included six modified multiple-choice questions from the Force Concept Inventory (FCI) questionnaire to measure students' thinking regarding motion [2] and six from the Commutative Assessments (CA) to measure students’ mastery of CT and related skills [21]. Following both tests’ completion, a self-efficacy survey consisting of a set of four statements was administered, modeled after Fidan and Tuncel's physics self-efficacy survey [22], regarding their mastery with motion concepts and a set of nine statements, modified from the Computational Thinking Self-Efficacy Survey [23], about their CT skills. Students indicated how much they agreed with each statement through a 7-point Likert Scale.

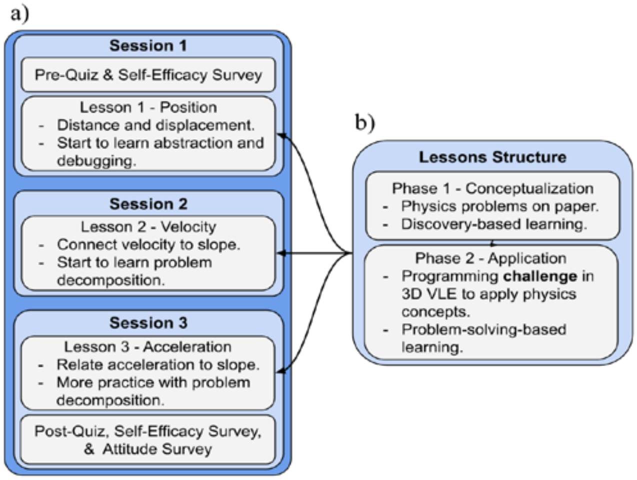


Figure 2. Structure of the week-long after-school club. During this week, the instructor went over three lessons covering physics concepts and CT skills. As the students progressed through the lessons, the difficulty of the programming practice in each of the lessons increased.

Finally, students completed an attitude survey consisting of six open-ended questions about views towards the curriculum and their physics classes, however only two of the questions are presented in this paper.

Furthermore, two questions from the physics section of the comprehension questionnaire were removed from the data analysis due to the questions having no clear correct answer when first administered, resulting in unequal maximum scores between the physics and CT sections. Due to the exemptions, each section's scores were adjusted to be a proportion of the maximum score for each domain. Similarly, self-efficacy survey scores were adjusted to match the points of the Likert scale used (i.e., the scores fell within 1 and 7).

Furthermore, the small sample size ($n = 4$) in this study induced low-power results in the Shapiro-Wilk test, preventing the assumption of normality for paired t-tests. The small sample size also prevented Wilcoxon's Signed Ranks test for matched pairs from giving significant results regardless of the difference between the two tests [24]. Considering these constraints, permuted t-tests for paired samples were used to determine any significant changes between pre- and post-tests, and the pre- and post-self-efficacy surveys. All analysis was performed in RStudio (Version 22.12.0+353) using the perm.t.test function in the MKinfer package (Version 0.9).

RESULTS.

In the physics portion of the questionnaire, there was an increase in scores between pre- and post-test scores. However, this increase was not statistically significant $p = 0.625$; Table I). On average, the students' normalized scores were 0.56 ($SD \pm 0.43$) in the pre-test and 0.63 (SD ±0.32) in the post-test. There was and no increase in the CT scores between the pre-test and the post-test ($p = 0.625$; Table I). The students scored an average of 0.75 ($SD \pm 0.21$) in the pre-test and 0.75 ($SD \pm 0.29$) in the post-test.

In the self-efficacy surveys, the students showed statistically insignificant growth in the physics section ($p = 0.125$; Table I). In this domain, the students started with a self-efficacy score of 3.69 ($SD \pm 1.34$) in and ended with a self-efficacy score of 4.81 ($SD \pm 0.52$) in the post. Inversely, there was a decrease in the students' scores for the CT portion of the survey, ($p = 0.625$; Table I). The decrease could be observed in the mean as the students went from getting a pre-self-efficacy score of 4.64 ($SD \pm 0.3$) to a post-self-efficacy score of 4.46 ($SD \pm 0.72$).

When asked to evaluate the club overall, 50 % of students were neutral, with 25% being slightly positive, and another 25% were positive. For their preference between traditional and club lessons, 50% of the students preferred their traditional classes and 25% slightly preferred their traditional science class. Only 25% of the students preferred the 3D-VLE.

DISCUSSION.

While there was an overall increase in the physics section, Student 1 and Student 3 saw a decrease of about 25% from their pre- to post-test scores. Looking at their responses, it appears that both students were viewing the incorrect figure. This is supported by Student 1 and Student 3 selecting the correct response for questions 3 in question 6; both questions had very similar responses and figures, with the only differences being the acceleration changed for velocity. Alternatively, it is possible that they developed a misconception about acceleration and velocity being indifferent, at least in how both are presented in a motion diagram. Future studies should analyze the students' thought process to determine if the cause was a misconception.

The lack of change seen in the CT scores could be explained by technical issues with the 3D-VLE during the study, which reduced the amount of time the students had during the application phase. This reduction in time prevented the students from growing their CT skills, especially considering that 75% of the students were already quite proficient. Regarding Student 2's decrease in their CT score, it should be noted that the student had to leave early halfway through Lesson 1 and was not able to attend the session 2, meaning that he only had the application phase during Lesson 3 to develop their CT skills. Additionally, Student 2 had not completed nor was currently enrolled in a computer science or programming course. Thus, the jump to model semi-complex phenomena in a simulation with little experience programming could have caused confusion and stagnated the development of their CT skills. As a result, only the learning gains of Student 1 could really be used as indication of how the curriculum allowed the students to develop their CT skills, considering the reduced time for programming in the 3D-VLE.

Physics concepts showed the largest jump in confidence, with students switching from neither confident nor doubtful about their mastery of physics concepts to being slightly confident about their mastery. The confidence changes of most students aligned with the change in their comprehension, except for Student 1. Student 1 saw a decrease in the physics section of the comprehension questionnaire by 25 percentage points, despite their confidence more than doubling (Table 1). It is possible that the student is confident about their commonsense beliefs, though further data is needed on the students' thought process to verify if this is the case.

Even more interesting are the cases seen with the student's confidence regarding their CT skills and practices. In general, the confidence in this domain saw a drop of over 1 point, with the post-test scores slightly increasing. Student 2 was the only student whose change in confidence aligned with the change in their comprehension. However, most students appear to underestimate their mastery of CT skills. For instance, Student 1 slightly increased in the CT section of the comprehension questionnaire, but their self-efficacy scores decreased by about 0.28. In an even more extreme case, Student 3 went from being slightly confident of their CT mastery to being slightly doubtful, even when the mastery appears to have stayed the same. These underestimations could be due to the lack of time during the application phase and thus lack of practice programming as a result of the technical problems. On the other hand, Student 4 increased their confidence by an entire point: shifting from being neither confident nor doubtful of their mastery to slightly confident of their abilities. Yet, the comprehension questionnaire was unable to capture that growth due to them already achieving the maximum score in the section, although it is possible that Student 4 did indeed continue dev-

Table 1. Comparison Between Individual Comprehension & Self-Efficacy Scores

Students	Comprehension				Self-Efficacy			
	Physics		Computational Thinking		Physics		Computational Thinking	
	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test
Student 1	0.50	0.25	0.67	0.83	2.00	5.25	4.71	4.71
Student 2	0.00	0.75	0.50	0.33	3.50	4.50	4.57	4.29
Student 3	0.75	0.50	0.83	0.83	5.25	4.25	5.00	3.57
Student 4	1.00	1.00	1.00	1.00	4.00	5.25	4.29	5.29

eloping their CT skills. A more extensive evaluation tool will be required to prevent this from happening in the future.

The mostly neutral attitude the students had towards the club could be a result of aspects of the curriculum and of the club itself. First, the club had 3 sessions in the same week, which might not have been seen as favorable by students. The technical problems encountered could have also caused some irritation and confusion among the students, since they were not able to apply their knowledge before moving on to the next lesson. Some of these negative views that the student might have towards the club could have been offset by aspects of the curriculum, such as the interactivity and novelty factor [7, 15].

While there are promising learning gains for physics, these preliminary results cannot be taken with full weight due to being statistically insignificant. However, addressing the limitations of this study could yield more significant and more promising scores. Take for example the study by Hutchins et al., in which the group using their C2STEM environment saw a greater increase in scores and learning gains across the Physics and CT domains [11]. Their study and the current study incorporated a problem-based learning approach, an introductory phase to familiarize the students with the physics concepts, and a modeling phase using the virtual environment. The key differences in these studies are the use of a 3D-VLE in the current study instead of the 2D-VLE used by C2STEM and the lack of limitations seen in the study by Hutchins et al.

As previously noted, 3D-VLE's have various advantages over 2D-VLE's [12-16], with some of the concerns with 3D-VLE's being addressed in the design of this study. Therefore, it could be safe to assume that the dramatically different results are not fully explained by the use of different environments, but rather by the limitations of each. First, it should be noted that the current study did not the use full curriculum that was developed due to time constraints. Second, the study by Hutchins et al. had a much larger sample size than the study described in this paper, which allowed them to utilize a quasi-experimental design. This larger sample size provided them with a more representative sample of high school students. Lastly, their study did not suffer from any technical issues with the environments and appears to have provided students with more time to complete each lesson. In turn, that extra time lack of issues prevented any confusions that could have hindered the students' learning while giving them the opportunity to apply what they have learned in the modeling phase. We, thus, believe that time should be added to the lesson in the current curriculum to allow students to take full advantage of the lessons and mitigate the effects of technical problems with the environments. These changes, combined with a new study containing a larger sample size and utilizing the entire curriculum, would provide greater learning gains and improvements in self-efficacy than the current study.

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