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The Impact of Physics Education Technology (PhET) Interactive Simulation-Based Learning on Motivation and Academic Achievement Among Malawian Physics Students

Herbert James Banda[1,2,3] · **Joseph Nzabahimana**[2]

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Abstract

The study investigated the impact of PhET simulation-based learning on students' motivation and academic achievement in learning oscillations and waves among Malawian secondary students. The following research questions guided the study: (i) What were students' motivation and academic achievement levels at the beginning of the study in oscillation and waves? (ii) To what levels do PhET interactive simulation-based learning impact students' motivation and achievement in oscillations and waves? (iii) Is the change in post-test scores due to the students' characteristics in non-randomized settings or the PhET interactive simulation-based learning? A sample of 280 (44.6% females) form three secondary school students with a mean age of 17.5 ($SD = 1.424$) from four schools in Blantyre urban district in Malawi was used in a quasi-experimental design of non-equivalent groups. The experimental group was exposed to PhET simulation-based learning, while the conventional teaching methods were used in the control group. Pre- and post-tests were used to collect data on academic achievement, and questionnaires collected data on motivation. Independent samples *t*-test showed a statistical difference between the two groups on post-test of the academic achievement. Results from linear regression indicated that the differences between the two groups in the post-test were not due to students' characteristics but rather the intervention with $p < 0.01$. The ANCOVA test on motivation constructs showed a significant difference with a small effect size between the study groups on self-efficacy, active learning strategies, performance goals, achievement goals, learning environment stimulation, and attitudes towards learning with computer learning. The results from the study suggest that PhET simulation-based learning improved the learning of oscillations and waves. PhET simulation-based learning provides visualizations and teaching aids that help easily understand content knowledge, hence improving students' academic achievement and motivation levels.

Keywords Academic achievement · Motivation · Oscillations · PhET simulation-based learning · Waves

✉ Herbert James Banda
herbertmembabanda@gmail.com;
hjamesbanda@luanar.ac.mw

Joseph Nzabahimana
jeef.nzaba@gmail.com

1 African Center of Excellence for Innovative Teaching and Learning Mathematics and Science (ACEITLMS), University of Rwanda-College of Education (UR-CE), P.O Box 55, Rwamagana, Rwanda

2 University of Rwanda-College of Education (UR-CE), P.O Box 55, Rukara Campus, Kayonza, Rwamagana, Rwanda

3 Basic Science Department, Lilongwe University of Agriculture and Natural Resource College, Bunda College, P. O Box 219, Lilongwe, Malawi

Introduction

The rate at which technological advancements are happening across the globe is a profound reason why the integration of computer-based instruction methods in education is a rapidly widespread trend (Lin et al., 2012). A closer look has to be given to the immense importance of learning through simulations and manipulation in education, particularly in Science, Technology, Engineering, and Mathematics (STEM) fields (Hensberry et al., 2018; Podolefsky et al., 2013; Whitacre et al., 2019). Eckhardt et al. (2013) defined computer simulations as interactive programs that exhibit models or systems of natural or artificial phenomena.

Interactive computer simulations offer an interactive and appealing interface enabled with functions of repeated manipulations and observations. These properties of the simulations help learners to repeat the videos or the experimental simulations a couple of times; hence, they develop a concrete understanding of the scientific phenomenon being exhibited by the simulation (Lin et al., 2012). Bozkurt and Ilik (2010), Banda and Nzabahimana (2021), and Otrel-Cass et al. (2015, 2016) noted that dynamic simulations help educators to facilitate the learning of physics concepts that are challenging and abstract and help students develop skills in virtual laboratory experimentation.

The internet market is infiltrated with many educational technology resources, software, and tools that can be used to facilitate the attainment of objectives in physics classes. One technology resource commonly used in physics classes is Physics Education Technology (PhET) interactive simulations because it has many features. PhET simulations are considered one of the best education software because they can be accessed for free online or downloaded and saved as web pages, jar files, or SWF files that can run on a flash player (Wieman et al., 2010). Furthermore, PhET simulations are research-based, highly interactive, animated, and easy to use. They create a game-like environment, can be used to model real-life scenarios, and do not need many computer specifications (PhET, 2021). PhET interactive simulation activities offer more to the way students learn physics in a way that intrigues the mind of learners with mouth-watering visualizations of abstract physics concepts; hence, they develop a deeper understanding of physics concepts (Ganasen & Shamuganathan, 2017; Perkins, 2020; Wieman et al., 2010). These features and advantages make PhET simulations ideal for physics in African schools as they can be easily incorporated into mainstream learning. They are cheap, considering the socio-economic status of schools in African countries.

Many studies have been conducted to establish the effects of computer simulations in science education. They have shown that computer simulations can improve the effectiveness of instruction, students' comprehension of the physics phenomenon, engagement, and experimentation in physics (Imbert, 2017; Li et al., 2014; de Jong et al., 2013; Otrel-Cass et al., 2015, 2016; Renken et al., 2016; Rutten, 2014; Rutten et al., 2012; Smetana & Bell, 2012). However, many of the studies in physics on the use of computer simulations involved the combination of two or more computer simulations. Some of these simulations have proprietary rights and are expensive for many secondary schools in Africa (Imbert, 2017; Smetana & Bell, 2012). This hinders the integration of computer simulations in many African education systems due to the costs. Moreover, research on PhET interactive simulations has focused much on virtual laboratory, inquiry learning, engagement, visualization, and conceptual understanding, particularly in general science (Aktamiş et al., 2016; Fan et al., 2018; Lazonder & Harmsen, 2016; Li et al., 2014; Lin et al., 2012; Liu et al., 2021; Smetana & Bell, 2012). Little research has been done to explore the effect of PhET simulation-based learning on academic achievement and motivation in physics education. A literature synthesis indicates that elements of motivation were measured partly and not entirely (de Vries & May, 2019; Gani et al., 2020; Mirana, 2016; Mrani et al., 2020; Prima et al., 2018; Sanchez et al., 2021). The study's findings on motivation have contributed to the misapplication of one element of motivation to umbrella the other elements. Hence, the studies made general conclusions concerning all elements of motivation (Sanchez et al., 2021). Similarly, studies on academic achievement have been done in biology, chemistry, computer studies, and mathematics (Ibezim & Asogwa, 2020; Lasisi et al., 2021; Nkemakolam et al., 2018; Talan, 2021); however, the impact of simulation-based learning on academic achievement in physics is under-reported. Lastly, despite the success of PhET simulations and other computer simulations in teaching and learning physics in Europe and Asia, little is known about PhET simulations in teaching and learning physics in secondary schools across African countries, with Malawi inclusive.

Literature Review

Motivation

Motivation is a crucial aspect of learning since it dictates how motivated or energetic a person is to accomplish a job. Educators have struggled to figure out what makes a pupil genuinely interested in learning. Many elements influence one's willingness to put effort into the learning process. These variables include a student's personality and talents, the qualities of specific learning activities, the surroundings, rewards, and the instructor's behavior (Slavin, 2018). It is a fact that all students are motivated in very different ways in the classroom. Students' motivation towards learning also ensures that students are engaged in activities; hence, meaningful learning is achieved.

Furthermore, motivation is also essential as it determines how much students will learn from the activities they are performing or the amount of information they will acquire. Motivated students develop skills on how to use their cognitive processes to absorb and retain information to apply in new learning situations. Gross (2010) and Myers (2011) perceived motivation as studying all the biological, social, and psychological pushes and prods that overcome peoples' laziness and move them eagerly or reluctantly towards action. From the definition of motivation aforementioned, it can be argued that motivation is a multifaceted phenomenon spanning from many things. Thus, motivation is a set of factors initiating and directing a person's behavior to attain the desired goal. Motivation is influenced by external and internal factors that range from goal orientation (learning and performance goals), achievement motivation, learned helplessness, teacher expectation, anxiety, and learning environment (Rolland, 2012; Senko et al., 2011; Slavin, 2018; Wentzel & Brophy, 2014).

In line with these factors, this study measured the constructs of motivation on the performance goal, learning goals, achievement goal, learning environment stimulation, active learning strategies, self-efficacy, and attitudes towards learning with computers. Students with learning goals take the purpose of school as acquiring generic competence skills and are more likely to use metacognitive or self-regulated strategies (Senko et al., 2011; Usher & Kober, 2012). At the same time, students with performance goals are solely driven to gain positive judgment of their competencies and neglect the negative judgment. They focus on acquiring good grades, easy marks, taking easy courses, and will give up instantly upon stumbling into challenging situations in the subject. Achievement goal is characterized by the student's desire and passion for succeeding. When they fail, they redouble the effort until they succeed. The learning environment and the implemented teaching methods determine how much the students will be motivated in the learning process. The kind of environment and teaching methods teachers use are crucial in determining students' motivation levels so that these factor levels up the classroom environment to meet the diversity in classrooms. Self-efficacy looks at how students apply skills and knowledge to execute behaviors vital to attaining the desired goals. This can be characterized by the ability to handle anxiety and stress. Attitudes towards learning with computers emphasize students' perception of using computers in learning physics.

Academic Achievement

Academic achievement is one of the significant ways a person's unique capabilities and potential can be measured and judged. According to Crow and Crow (1969), as cited in Cheng et al. (2019), Dhull and Rohtash (2017), and Maya et al. (2021), academic achievement refers to what extent a learner is profiting (gaining) from academic instruction in a prescribed learning area. How much of a particular trait, skill, and knowledge students have accumulated and acquired through learning explains academic achievement (Bhat, 2013). Every learning situation has a set of prescribed goals that students have to achieve, and this acts as a reference point for what students have acquired upon finishing the learning process. Cheng et al. (2019) discussed academic achievement as the academic performance of a student. Academic achievement can be deduced from the test score that a student has gotten in a school subject. Through ability tests, students' overall academic achievement can be understood (Fan & Chen, 2001). From this, it can be discussed that academic achievement is the attainment of the prescribed goals (trait, skill, and knowledge) during the learning process, as shown in the test score.

PhET Simulation-Based Learning

PhET simulation-based learning involves using PhET simulations in instruction. PhET simulation-based learning is blueprinted in the following aspects or characteristics: (i) Presence of formalized, manipulatable simulation or model is characterized by formalizing physics concepts into models and running them as computer programs. The models are formalized with quantitative or qualitative characters, and most simulations combine both. Usually, quantitative simulations have variables and parameters which are incorporated into a numerical model (Krobthong, 2015; Peffer et al., 2016; Sarabando et al., 2011). Qualitative models have components of models and relations that are represented structurally or symbolically. Qualitative simulation models are not purely numerical. Learners manipulate variables and parameters in the model and observe the outcomes on the screen. (ii) Outline of learning outcome involves delineating expected learning goals. The goals can be as follows: (a) conceptual knowledge acquisition, acquiring the underlying principles and concepts of the phenomenon. (b) Operational knowledge attainment in the form of cognitive and psychomotor skills. (c) Developing virtual experimentation and analytical skills. (iii) Elicitation of the specific learning process, for example, hypothesis generation and testing. Learners must generate their working hypothesis and test it to create an understanding. Eventually, learners can develop or acquire conceptual and operational knowledge through a constructive approach. This stage also involves planning and monitoring to ensure effective learning is happening. (iv) Learner activity enhanced by simulation models is framed by giving learners tasks that involve manipulating something in the PhET simulation. This involves identifying, setting up parameters and variables, and defining what variables will be output. Learners also make sense of the findings and results by comparing the set hypothesis and implications. (v) Modeling involves adding, deleting, or altering variables and parameters in a model. Modeling involves going beyond varying values of variables and parameters. Students are engaged in higher-order tasks of designing, modifying, adding, or editing properties of a model. The aforementioned attributes work in unison to define and establish the design of PhET simulation-based learning and instruction.

Learning through exploration enhanced by simulation has high demands on student cognitive engagement. Facilitators must scaffold the learning process through consolidation. This is important as it helps make learning efficient and effective.

Theoretical Framework - the Cognitive-Affective Theory of Learning with Multimedia (CATLM)

Roxana Merono founded the CATLM in 2006, and it is an extension of Richard Mayer's cognitive theory of multimedia learning (Moreno, 2007). The primary premise of multimedia learning research is creating multimedia instructional messages. Multimedia instruction is designed in line with how the human mind works to lead to more meaningful learning. The CATLM centers on these assumptions to mediate the learning process: (i) the affective mediation hypothesis, which highlights that the affective and motivation factors mediate the learning process; (ii) the metacognition hypothesis assumes that metacognitive processes mediate the learning process; (iii) long-term memory is divided into past experiences and the general domain knowledge which can be defined as episodic and semantic systems; (iii) the assumption that individual differences associated with students' prior knowledge, cognitive styles, and abilities influence students gains brought about by the instruction strategy and resource or media; (iv) the human information processing system includes dual channels for visual/pictorial and auditory/verbal processing; (v) each channel has a limited capacity for processing; and (vi) active learning entails performing a set of coordinated cognitive processes. In the context of this study, exposing students to PhET interactive simulations in the teaching and learning of physics enabled students to activate their visual systems, which will more likely enhance their capacity to retain more information, or students' cognitive engagement will increase or decrease; hence, this will impact the academic achievement.

Moreover, PhET simulation-based learning impacts the affective and motivation factors that mediate the learning process by increasing or decreasing students' motivation levels. According to the above theory, when information is dual-coded, the chances of retrieval increase, and students' motivation levels change. Moreover, CATLM supports the active learning assumption and advocates for learners to be at the center of learning and be in charge of creating ideas and knowledge (Hinde & Perry, 2007).

Studies on Motivation and PhET Simulations in Physics

Mrani et al. (2020) documented the integration of PhET simulations in the teaching and learning of physical science of common core (Morocco), underscoring that PhET simulations are remarkable in helping students acquire new understanding and learning of common core science. Post-survey and follow-up questions to get the students' insights, perceptions, and opinions about PhET simulations helped them note that PhET simulations enabled students to improve their engagement, interactivity, and motivation. This made them suggest further studies on the impact of PhET simulations on motivation and engagement.

Mirana (2016) and Prima et al. (2018) noted a moderate change in motivation among students in the experimental group due to PhET simulation learning. They both highlighted the need to extend motivation parameters to include motivation factors on active learning strategies, learning environment stimulation, and other factors that affect motivation could also be measured in their entirety since motivation is a multifaceted phenomenon.

Doster and Cuevas (2021) measured the impact of computer-based programs on motivation using a questionnaire on elements of competence and efficacy, goals for reading, and social purposes for reading. They noted that motivation slightly changed. This indicated that motivation was measured partially; hence, a study to measure the other elements of motivation can substantiate the findings in this area.

Studies by Gani et al. (2020) and de Vries and May (2019) underscored that students improved conceptual understanding, problem-solving skills, and motivation when taught by computer simulations in teaching physics and chemistry. However, both Gani et al. (2020) and de Vries and May (2019) did not clarify the instrument they used to measure motivation and which elements of motivation were being measured. This suggests that studies should be instituted to understand motivation and computer simulations in physics to understand the factors that influence motivation fully.

The literature analysis on motivation and computer simulations hastily indicates that computer simulations are vital in improving learners' motivation in physics classes. However, thorough synthesis of the literature indicates that elements of motivation were measured partly and not in their entirety (de Vries & May, 2019; Gani et al., 2020; Mirana, 2016; Mrani et al., 2020; Prima et al., 2018; Sanchez et al., 2021). The study's findings on motivation have contributed to the misapplication of one element of motivation to umbrella the other elements. Hence, the studies made general conclusions concerning all elements of motivation (Sanchez et al., 2021). That is, a study encompassing and measuring all the elements of motivation on computer simulations is needed as it establishes a comprehensive understanding of the knowledge in this field.

Studies on Academic Achievement and PhET Simulations

Computer simulations are highly effective compared to the traditional instructional design of teaching. A 6-year longitudinal study by Guy and Lownes (2015) revealed a remarkable improvement in undergraduate students' performance using the computer simulation hybrid format compared to those taught using the conventional method in a microcomputer application course. Guy and Lownes (2015) conceived that more research needs to be done at different educational levels and environments to establish validity.

Hannel and Cuevas (2018) study on science achievement and motivation compared computer-based laboratory and traditional hands-on manipulation in primary school. They found that physical and computer-based laboratories helped increase students' knowledge base and retain new information. However, neither method was more beneficial than the other. Furthermore, they admitted that further studies need to be conducted at higher levels since participants were from middle school.

Batuyong and Antonio (2018) focused on developing and finding the effect of PhET interactive simulation-based activities in electromagnetism on the student's performance and learning experiences. The findings from the study indicated that PhET simulations should be recommended to be used in classroom instruction to increase students' understanding of physics concepts. The research study by Batuyong and Antonio (2018) emphasized little on the performance but the validity of PhET simulations on the teaching and learning outcomes, instructional characteristics, and evaluation.

Koh et al. (2010) studied the impact of 3D simulation learning on engineering students' performance and motivation. They noted that students in the experimental group had higher post-test scores than the control group. Similarly, the motivation levels in the experimental group were also higher. The findings in this study laid forth a significant background on motivation and performance in STEM fields. They indicated the need for studies in secondary and primary schools on the impact of 3D simulation learning on performance and motivation.

Potane et al. (2018) and Mallari and Lumanog (2020) noted that PhET simulation learning significantly impacted academic achievement among students in science. Potane et al. (2018) and Mallari and Lumanog's (2020) studies could not be generalized as the study samples were small ($n=40$ and 80), respectively. They suggested the need for studies with larger samples with randomized designs.

In Kenya, a study on the effect of using computer simulations on performance was done by Chumba et al. (2020). They found that computer simulations led to improved student performance. They acknowledged that similar research should be conducted in secondary schools in other African countries to provide coherent and comprehensive findings on the effectiveness of PhET simulations in the African context.

Context of the Study

Malawi follows an 8–4-4 system of education. Students spend 8 years in primary school, 4 years in secondary school, and 4 years of a general college degree; this excludes engineering and medicine programs (MoEST, 2008). Physics in primary schools is learned as a general science subject, and it is mandatory. In secondary schools, physics is a mandatory subject in the first 2 years (junior section) and an optional subject in the senior section (2 years). In college studies, physics is a mandatory subject in all science programs in the first year (MoEST, 2008).

Reports from Malawi National Examination Board) show that there is a decrease in the number of students enrolling in physics in senior secondary school, lack of interest in physics, and poor performance of students in physics in the national examination particular in the topic of oscillations and waves. MANEB (2017, 2018, 2019a, b) revealed poor performance on questions related to oscillations and waves compared to other topics in physics in the national examinations. Lastly, motivation is another factor impinging physics learning in Malawi. Many students are losing interest in it due to its abstract nature and the teaching styles and materials or resources teachers use (Hollow & Masperi, 2009; Mwale & Bahati, 2021). As cited in Batuyong and Antonio (2018), studies have shown that students hardly understand and are demotivated to learn physics content due to a lack of physical models or representations of the invisible concepts.

This poses a great task to educators in physics to reinvent the wheel of teaching by developing exciting and meaningful ways to facilitate learning. When used efficiently, simulation-based learning strategies can overcome the problems of interest and academic achievement in physics. As Eckhardt et al. (2013) underscored, simulations can help educators teach by capturing and sustaining students' attention more directly through the visual display of the phenomenon. Thus, integrating PhET interactive simulations in physics classes ought to be one of the remedies for correcting poor academic achievement and lack of motivation towards physics, particularly oscillation and waves by students in Malawian schools.

According to Hollow and Masperi (2009), ICT is mainly used to facilitate clerical activities, process examinations, timetabling, and keep student records in Malawi. Schools teaching computer studies as a subject are the only schools where learners interact with the computer for a limited time in class, and many students usually fail to operate the computer due to a lack of more practical time (Hollow & Masperi, 2009). The integration of ICT in education is backlash in schools as many teachers do not have access to many education software due to their cost as well as lack of information about open educational resources (Gondwe, 2020, 2018; Hollow & Masperi, 2009; Mwale & Bahati, 2021; Nyirongo, 2009). Thus, little research has been done in Malawi on integrating ICT in secondary schools; hence, it is a field that must be explored (Gondwe, 2020, 2018; Nyirongo, 2009). Based on the reviewed literature, it can be said that a research study on the impact of PhET simulation-based learning encompassing all the elements of motivation and academic achievement in Malawi is needed to address the gap highlighted in the literature. The following research questions guided the study:

(i) To what levels do PhET interactive simulation-based learning impact students' motivation and achievement in oscillations and waves?
(ii) Is the change in post-test due to the students' characteristics in non-randomized settings or the PhET interactive simulation-based learning?

Methodology

Participants and Sampling Methods

Purposive sampling techniques were used to select the schools involved in this study. Out of 36 schools, four were selected purposively as they all had well-furnished computer laboratories and were close to the central business district. The schools chosen to participate in the main study were selected considering that teachers, students, school facilities, and school performance were comparable. To achieve this, the school sites were visited and checked prior to the beginning of the main study. Additionally, records of schools' performance in national examinations were checked, and it was established that the schools that participated in the main study had a comparable academic performance. Four teachers who were all qualified teachers (bachelors degree) with at least greater than 5 years of teaching experience were involved in this study. The total number of the sample was 280 students. The sample comprised 155 (55.4%) males and 125 (44.6%) females with a mean age of 17.5 years ($SD = 1.424$). The control group had 136 students (76 males), while the experimental group had 144 students (79 males). Even though participants are self-selected by their school. The participants represent a diverse and representative sample as placement into the schools was done randomly. A pre-test was administered at the beginning to establish the study's baseline and determine if both groups' levels of motivation and academic achievement were equal.

Measures

Data on academic achievement was collected using the same pre-post-test. The researchers designed the pre-post-tests by adapting questions from physics Malawi National Examination past papers and physics books approved by Malawi's ministry of education and science. The tests were composed of 16 structured items (open-ended questions) on oscillations and waves with Cronbach alpha, $\alpha = .78$, within the recommended range (Cohen, 1988). The experts from the University of Rwanda Department of Physics and the participating teachers established content and face validity. They scrutinized the test items regarding the objectives in the physics syllabus and the content on oscillations and waves. The motivation questionnaire with $\alpha = .856$ was adapted from Tuan et al. (2005) and Knezek and Christensen (1996). The questionnaire was adapted by replacing the word *science* with *oscillation and waves* to measure students' motivation in oscillation and waves. The adapted questionnaire had 38 items measured on a 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree). It contained subscales measuring self-efficacy, active learning strategies, physics learning value, performance goal, achievement goal, learning environment stimulation, and attitude towards PhET simulations in teaching and learning. The study instruments were piloted on 49 students in two schools before starting the study to establish content validity.

Study Design and Procedures

Data for the main study was collected in 6 weeks using questionnaires and pre-post-tests. Quantitative research methods guided the study to determine the impact of PhET simulations on students' motivation and academic achievement in the teaching and learning of oscillation and waves. Since it is a quantitative approach, the study employed the survey design (questionnaire) to measure the effect of PhET on motivation and the pre-post-test to measure the effect of PhET on students' achievement. A quasi-experimental design of non-equivalent (pre-test and post-test) control-group design was used as it is convenient considering that the purposive sampling technique was employed to select the schools. It was hard to mix two control/experimental groups from different schools into one, considering the classroom space (social distance due to COVID-19 measures). However, students' placement in all schools was randomly done by the selection criteria used by the schools. The non-equivalent control-group design involves the experimental group A and the control group B selected with no random assignment. At the beginning of the study, both groups were exposed to a pre-test and pre-questionnaires to test for academic achievement and motivation, respectively, to establish the baseline levels of students in academic achievement and motivation before the study. Later, the two groups were exposed to the same teaching and learning objectives on oscillations and waves. The two groups used the same books and notes in learning oscillation and waves. The experimental group was only exposed to teaching and learning through PhET interactive simulations. The students in the experimental group were involved in active learning methods as they used in their normal classes (experiments, group discussions, inquiry learning, and collaborative learning) enhanced by PhET simulations depending on the lesson's learning objective. The control group was also taught using the same active learning methods as in their normal classes (experiments, group discussions, inquiry learning, and collaborative learning) with no enhancements by the PhET simulation. Each teacher was teaching their class in their respective schools to control the Hawthorne effect. The experimental group was learning in the school computer laboratory room with working computers totaling forty (40). Each student in the experimental group had a computer on which they were working. In each lesson, tasks on oscillations and waves were aligned with the attributes of PhET simulation-based learning. Students were given learning instructions that they had to follow and observe and understand the simulation's physics phenomenon. PhET simulation-based learning was implemented in classrooms by the following teaching and learning steps. (i) Outlining the learning outcome and probing students to elicit their prior knowledge of oscillations and waves. (ii) Elicitation of the specific learning process, for example, hypothesis generation and testing. Learners generated their working hypothesis and tested the hypothesis in PhET simulations to create an understanding. (iii) Learners make sense of the findings and compare them to their hypothesis. (v) The facilitator consolidated the learning process and recommended further testing and manipulating the PhET simulations to get more insights into the concepts. Consolidation was in the form of questions, demonstration, and classroom activities to add to the concepts that were missed by the student or unclear. Six weeks later, the groups were subjected to a post-test and a post-questionnaire on motivation similar to the one they took before the teaching and learning process.

Since the study used the non-equivalent control group design, which does not follow random assignment of samples into groups, the researchers controlled the nonequivalence among students by regression method in data analysis. As recommended by Theobald and Freeman (2014), data were also collected on measures to investigate if the differences in post-test scores between the groups are due to students' composition (student characteristics) or the treatment in non-randomized studies. The data were collected on measures that reflect students' ability and preparation (students characteristics) which were considered to be: (i) students' prior knowledge about oscillation and waves (pre-test); (ii) students' understanding of the larger discipline (end of term aggregate score); (iii) student work habits and study skills (the previous end of term physics score); and (iv) the intervention (treatment = 1 if the student is in the treatment class, treatment = 0 if the student is in the control class). Measures of students' prior knowledge about oscillations and waves were collected by pre-testing before the study. Intervention (treatment) measures were collected during the research study period. Measures of students' understanding of the larger discipline are the end of term aggregate score, and student work habits and study skills are each student's previous end of term physics score from the previous term (Theobald & Freeman, 2014). This was internal data about the participants collected from the participating schools' data system by requesting through proper channels for research purposes after the post-test.

Data Analysis

The achievement test had 16 open-ended questions. Test items were graded differently based on the test item level of Bloom's taxonomy. The answers were graded as follows: 0 = wrong answer, 1 = partial correct answer, 2 = good, 3 = very good, 4 = excellent. The total test score was 75. The total score of each student was calculated out of 75 and converted to a percentage. The percentage of the score on the pre-test and post-test is used in the *t*-test. The independent *t*-test was used to determine the differences in the pre-post-tests between the groups. The effect size was calculated using Cohen's *d* test. The linear regression method was used to determine if the groups' change was due to the intervention, not the students' characteristics on the academic achievement test. Using the student linear regression model formalizes the intuition that assumes that an outcome (post-test) is a linear function of the explanatory variables and the intervention. The motivation questionnaire had 38 closed-ended questions, which were divided into subscales. The total score on each subscale was calculated, and a mean score was calculated for each subscale to represent the overall score of that subscale (construct). The mean score of the subscale (construct) on the first survey is compared to the mean score of the construct on the second survey in ANCOVA. ANCOVA test analyzed the motivation questionnaire with the post-test as the dependent variable and the pre-test as the covariate. ANCOVA was identified to suitably control the within-group error variance and mediate the effect of the covariate. IBM SSPS version 26 package was used to analyze the data.

Results

The Effect of PhET Simulation-Based Learning on Students' Academic Achievement

The descriptive statistics on the pre and post-test on academic achievement were analyzed. Data were analyzed using a *t*-test followed by linear regression after it met the normality test using Shapiro–Wilk (pre-test: $p = 0.142$, post-test:

Table 1 Descriptive statistics of the pre- and post-test between the groups on academic achievement

Group	Pre-test			Post-test		
	Mean	*N*	Std. deviation	Mean	*N*	Std. deviation
Control	47.28	136	7.464	52.90	136	8.555
Experimental	47.22	144	7.076	63.85	144	10.598

$p = 0.112$) on academic achievement. The descriptive data of the pre-test and post-test on academic achievement was analyzed and presented in Table 1.

The mean on the pre-test of the control group was 47.28 ($SD = 7.464$), and the experimental group was 47.22 ($SD = 7.076$). An independent sample *t*-test on the pre- and post-test scores was done, and the results are presented in Table 2.

A *t*-test of independent samples on the pre-test showed no significant difference between the control and experimental groups with **t (278) = −0.066, p = 0.883** with the lowest Cohen's *d* value of 0.0079. The pre-test scores were not different between the groups.

The independent sample test of the post-test between the groups showed significant changes between the group, **[$t(271.497) = 9.532, p < 0.01$]**. Cohen's *d* test was calculated to find the effect size of the treatment in this study. It was calculated using the formula from Rosnow and Rosenthal (1996). The effect size of the treatment calculated from the formula was 1.14, which is a very large effect size of the treatment. An effect size of 1.14 indicates the experimental group's mean at the 86 percentiles of the control group (Fritz et al., 2012; Rosnow & Rosenthal, 1996). The Cohen's *d* of 1.14 is a 62.2% nonoverlap of the test score distribution between the participating groups (Cohen, 1988).

Regression Method to Determine if it is the Treatment or the Students' Characteristics Student linear regression model was used to test if the results of *t*-test significance were due to the treatment or the students' characteristics in this non-randomized study (Theobald & Freeman, 2014). The assumptions of normality in the regression were all tested and met. The adjusted *R* square value of the model summary of the linear regression is 40.9% which suggests that the model is a good fit (Cronk, 2020). The independent variables explain 40.9% of the dependent variable. The model summary of the linear regression indicates that it is significant with a *p*-value of 0.000.

Table 2 Results of the independent sample *t*-test of the pre- and post-test between the two groups

	t-test for equality of means				
	t	df	*p*-value	Mean difference	Cohen's *d*
Pre-test mark(%)	0.066	278	0.883	0.057	0.00792
Post-test marks (%)	9.474	278	0.000	10.943	1.14

The ANOVA output of the regression analysis showed that the model is a significant model with $p < 0.01$. The ANOVA results from the regression analysis indicate the test statistics of $F(4,275) = 25.984$, $p < 0.01$ inferred that the independent variables are good predictors of the dependent variables. Table 3 shows the estimated coefficients of the linear regression model.

Table 3 provides the fitted regression model that is:

$$\begin{aligned}\text{Post test} = {} & 48.13 + 0.214 * \text{Pretest marks} \\ & - 0.104 * \text{end of term physics score} \\ & + 0.001 * \text{end of term aggregate marks} \\ & + 10.856 * \text{treatment}\end{aligned}$$

The coefficients of the regression model are interpreted as follows:

The Constant. The estimated intercept (constant = 48.133) means that the expected score of a student on the post-test who did not take the intervention has average pre-test marks, average aggregate end of term score, and average end of term score in physics 48.133.

Pre-test marks. For every point added in the pre-test by the student, the post-test increases by 0.208 or else equal, and the relationship between the pre-test and post-test is not significant (*p*-value = 0.207).

End of Term Physics Score. A one-unit increase in the end-of-term physics score resulted in a 0.039 increase in the post-test, and the relationship between the end-of-term physics score and the post-test is not significant (*p*-value = 0.059).

End of Term Aggregate Score. An increase at the end of term aggregate score by one-unit results in an increase in post-test by 0.135, and the relationship between the end of term aggregate score and post-test is not significant (*p*-value = 0.107).

Treatment. For every additional point in the treatment scale, there is a 10.856 increase in the post-test score, and the probability that the treatment and the post-test are related is significant, with a *p*-value of less than 0.01. Thus, the regression method shows that post-test scores

Table 3 Estimated coefficients of the student's linear regression model

Model		Unstandardized coefficients		Standardized coefficients	*t*-value	*p*-value
		Beta	Std. error	Beta		
1	(Constant)	48.133	5.570		8.642	0.000
	Pre-test marks (%)	0.214	0.079	0.140	2.727	0.207
	End of term physics score	−0.104	0.055	0.099	1.895	0.059
	End of term aggregate marks	0.001	0.008	0.006	0.107	0.915
	Treatment	10.856	1.182	0.490	9.185	0.000

A Dependent variable: post-test marks (%), *p*-value at 0.05 below

are significantly influenced by the treatment given to the students by a magnitude of 10.856 with each increase in the treatment.

The Effect of PhET Simulation-Based Learning on Students' Motivation

The data on the second objective on the influence of PhET simulation-based learning on motivation was analyzed descriptively and inferentially through one-way ANCOVA. The test of normality was done by using Shapiro–Wilk on all constructs. The following were the means of the constructs on motivation in the pre-survey (Table 4).

Descriptively, the means of the constructs between the two groups were not different in the pre-survey. The overall mean of motivation in the experimental group was 3.33, and the control group was 3.34 in the pre-survey. The post-survey questionnaire data were analyzed descriptively by finding the mean of each construct. The table presents the descriptive statistics on the post-test between the groups.

Table 5 shows that the motivation levels were higher in the experimental group than in the control group. One-way ANCOVA was used to determine the significant difference between the groups. The pre-survey was the covariate, and the post-survey was the dependent variable with the group as the fixed factor.

The results of the ANCOVA analysis on post-survey self-efficacy indicated a significant difference in mean [$F(1,271) = 43.744$, $p < 0.01$] between the groups while adjusting for pre-survey self-efficacy. The partial Eta squared (η_p^2) value was 0.139, a small effect size. Thus, the treatment explains 14% of the post-survey self-efficacy construct.

There was a significant difference in the post-survey construct of active learning strategies [$F(1,271) = 83.278$, $p < 0.01$] between the groups with a small size effect (η_p^2) of 0.235 (24%). The construct of physics learning value on post-survey showed a significant difference between the means of the groups [$F(1,271) = 45.074$, $p < 0.01$], with a size effect (η_p^2) of 0.143 (14%). The analysis of the post-survey construct of performance goal indicated a significant difference between the groups of [$F(1,271) = 39.448$, $p < 0.01$], with a small size effect (η_p^2) of 0.127 (13%). The construct of achievement goal on post-survey found that there was a significant difference between the groups of [$F(1,271) = 60.292$, $p < 0.01$], with a small size effect (η_p^2) of 0.182 (18%). The analysis of the post-survey construct on learning environment stimulation indicated a significant difference between the groups of [$F(1,271) = 78.186$, $p < 0.01$], with a size effect (η_p^2) of 0.224 (22%). The attitude towards learning with computers construct in the post-survey registered a significant difference between the groups with a [$F(1,271) = 48.058$, $p < 0.01$], and a large effect size (η_p^2) of 0.51 (51%).

Table 4 Descriptive statistics of the motivation construct on pre-survey between the two groups

Construct	**Group**			
	Experimental (*n* = 144)		**Control (*n* = 136)**	
	Mean	Std. deviation	Mean	Std. deviation
Self-efficacy	3.09	0.692	3.10	0.545
Active learning strategies	3.35	0.852	3.36	0.871
Physics learning value	3.29	0.965	3.39	0. 985
Performance goal	3.16	0.796	3.12	0.799
Achievement goal	4.27	0.702	4.29	0.656
Learning environment stimulation	3.05	0. 712	3.03	0. 782
Computer attitude learning	3.12	0. 949	3.10	0.904

Table 5 Descriptive statistics of the motivation construct on post-survey between the two groups

Construct	Group			
	Experimental ($n = 144$)		Control ($n = 136$)	
	Mean	Std. deviation	Mean	Std. deviation
Self-efficacy	3.11	0.799	2.95	0.769
Active learning strategies	3.96	0.587	3.17	0.821
Physics learning value	3.96	0.555	3.21	0. 775
Performance goal	3.16	0.796	2.98	0.798
Achievement goal	4.27	0.407	3.76	0.450
Learning environment stimulation	4.04	0. 573	3.40	0. 584
Computer attitude learning	3.53	0. 349	2.85	0.324

Discussion and Conclusion

The study's primary purpose was to determine the impact of PhET simulation-based learning on students' academic achievement and motivation on oscillations and waves among Malawian secondary school students. An analysis of data on students' motivation and academic achievement levels when learning oscillations and waves indicated that the levels of academic achievement and motivation were the same at the start of the study and on the pre-test.

The analysis of the impact of PhET interactive simulation-based learning on students' motivation and academic achievement in oscillations and waves suggests that PhET simulation-based learning can improve academic achievement and motivation among learners. The data analysis conducted in this study has established that learners in the experimental groups have significant gains compared to learners in the control group on academic achievement.

The Cohen's *d* test on the *t*-test showed a remarkably higher effect size of 1.14, depicting that the differences in the scores of the students between the groups could arise due to the treatment. A further test was done to analyze if the changes in the scores of the student were due to the student characteristics (composition) or the treatment in quasi-experimental studies (Theobald & Freeman, 2014). The results from the regression method showed that the changes in the student's scores were due to the treatment. The regression method showed that the treatment (intervention) was statistically significant ($p < 0.01$) with the student post-test score and increased the score on the post-test by 10.856 units on every unit increase in the treatment.

The study contributes one of the best possible ways or methods of intervention to elevate the academic achievement levels of students in oscillations and waves. This observation is in line with the findings by Fan et al. (2018), Ganasen and Shamuganathan (2017), Gunhaart and Srisawasdi (2012), Rutten et al. (2012), and Smetana and Bell (2012), who noted the significance of computer simulation interventions on enhancing meaningful learning. PhET simulation-based learning improves students' understanding of content knowledge, impacting their academic achievement. Hence, the study brings to light how PhET simulation-based learning can impact academic achievement among learners and their overall learning. Student's performance in the experimental group after the intervention (treatment) underscored the significance of using PhET simulation-based learning to engage learners' minds and efficiently stimulate them to be more receptive to new information. Moreno (2006, 2007) suggested in the cognitive-affective theory of learning with multimedia (CATLM) that pictures, dynamic visuals, animations, and simulations activate visual systems in the human body, enhancing a person's capacity to retain more information and increasing cognitive processes.

The experimental group learning was exposed to PhET simulation-based learning to foster visualization by using dynamic visualizations and cement understanding of content knowledge in oscillation and wave concepts. The study's results suggest that using PhET simulation-based learning in learning oscillations and waves as multimedia impacted the way learners visualize, understand, and conceptualize oscillations and wave concepts. The results in Table 3 on the estimated coefficients of the student's linear regression model highlighted that the treatment impacted the post-test scores significantly. This allowed students to develop a positive attitude, confidence, active learning skills, and scientific thinking. They started approaching physics as a subject that could be easily understood; hence, students improved performance in achievement tests in the experimental group. Thus, learners developed a good understanding of the content knowledge they could easily apply to the achievement test. The study's findings align with studies by Banda and Nzabahimana (2021), Batuyong and Antonio (2018), Chumba et al. (2020), and Potane et al. (2018), who noted that PhET simulations are very good instructional materials in teaching to help improve students' performance in physics.

The research study further explored the impact of PhET simulation-based learning on motivation between the experimental and control group. The analysis of the seven motivation constructs suggests that PhET simulation-based learning significantly impacted the affective domain of motivation as conceived in this study in the learning process. The results from the analysis with ANCOVA indicated that PhET simulation-based learning improved the self-efficacy, active learning strategies, physics learning value, performance goal, achievement goal, learning environment stimulation, and attitudes towards learning with computers significantly with p-values of less than 0.01 and with a small size effect in all constructs. This entails that PhET simulation-based learning can improve students' affective learning domain of motivation by capturing their attention, interest, engagement, interactivity, and desire to be more involved in the oscillation and wave learning process. PhET simulation-based learning sparked the experimental group's curiosity, interest, interactivity, and motivation. After classes, students were observed to ask for laboratory permission to interact and play with PhET simulations to cement the learning. This increased students' motivation and engagement in the experimental groups. Students in the experimental group were highly motivated and explored the simulations further after classes. They formed questions for the next lesson from observations made when carrying out independent investigations during their free time with the PhET simulations. This denoted improvement in active learning strategies and attitude towards using PhET simulations in oscillations and waves. PhET simulation-based learning also sparked the development of inquiry skills in the students, as noted through the improvement in active learning skills among students in the experimental group. The study's findings agree with studies conducted by Koh et al. (2010), Mirana (2016), and Prima et al. (2018) on improving motivation aspects of self-efficacy, engagement, achievement goals, and performance goals. Students' energy, focus, and drive were increased towards achieving learning objectives in the experimental group. The items under the construct of attitude with PhET simulation-based learning measured students' engagement, interest, and attention span in the learning process. Students' energy, focus, and drive were increased towards achieving learning objectives in the experimental group. Students in the experimental group were more engaged, interested, and motivated, making the learning of oscillations and waves lively as shown by the ANCOVA analysis on the construct of attitude towards learning with PhET simulations which measured items on interest, engagement, and attention span. The ANCOVA analysis on the construct of attitude towards learning with PhET simulations in the post-survey registered a significant difference between the groups and a large effect size.

This impacted the active learning skills; hence, they were more focused, and the learning was meaningful. However, Hannel and Cuevas (2018) noted no significant differences between the groups on motivation levels. They underscored that motivation remained consistent throughout the study between the groups. One of the reasons attributed to Hannel and Cuevas (2018) findings is the time given to students to manipulate the computer simulations; hence, the students did not have the whole experience of computer simulations.

This study contributes to the literature on computer simulations in physics education by demonstrating the viability of PhET simulation-based learning to enhance academic achievement and motivation in developing countries. The research adds knowledge on how computer simulations can improve students' affective and cognitive domains during the learning process to enhance academic achievement, engagement, interactivity, motivation, and the thought process of meaning-making in Malawi schools. The study also adds to the literature on ICT integration in education in Southern Africa, which is still developing.

The findings of this study are very significant to the education system of Malawi, countries in southern Africa, and the world, as this study has shown how fundamental the use of PhET simulations is in enhancing motivation and academic achievement among physics learners. Students' engagement, curiosity, interest, and academic achievement were raised throughout the study. They had the chance to see abstract concepts in physics being portrayed very easily compared to how they are portrayed in physics books. Moreover, PhET simulations are free; hence, schools can easily access them to compensate for the shortages in physical laboratories (Farrokhnia & Esmailpour, 2010; Gunhaart & Srisawasdi, 2012; Marces & Caballes, 2019; Simon, 2014).

The Implication of the Study

Integrating PhET interactive simulation-based learning improved physics students' academic achievement and motivation in the experimental groups more than in the control group. The improvement of academic achievement and motivation towards oscillation and waves by the students in the experimental group explains how PhET simulation-based learning positively impacts the cognitive and affective domain of motivation envisioned in the variables measured in this study. The results from the study suggest that PhET simulation-based learning improved the learning of oscillations and waves by laying forth visualizations that helped in quickly understanding content knowledge hence more improvement in academic achievement (Koh et al., 2010; Moreno, 2007). Thus, if teachers can explore and align PhET simulations to physic topics and objectives in their syllabus, physics learning can be easily done as abstract and complex concepts will be explained with demonstrations and visualizations from PhET simulations hence more meaningful learning as stipulated in the CATLM (Moreno, 2007). The results from the study suggest that PhET simulation-based learning improved oscillation and wave learning by making the learning process more contextualized, meaningful, and matching to the learners, an environment filled with dynamic visualizations.

Recommendations of the Study

The study recommends that schools owning computer laboratories be equipped with skills in integrating PhET simulations in teaching and learning oscillations and waves and other physics topics. That will enhance the development of cognitive and affective domains in the learning process, as supported by the study results and cognitive-affective theory of learning with multimedia (CATLM). Secondly, the study recommends that teachers in Africa be exposed to the sea of free educational resources through computer simulations like PhET simulations to maximize learning experiences. Again, the study suggests that efforts be put into training teachers to integrate PhET simulations and other simulations into active learning designs for the students to attain academic goals. Lastly, this study calls on educators in Africa to explore PhET simulations contextualized for their local language and other computer simulations to clarify abstract concepts to enhance understanding of oscillations and waves and other topics in active learning designs.

The researchers noted the need for further studies on the impact of PhET simulation-based learning on motivation and academic achievement in terms of gender. Research in this area is lagging. It should be noted that this study did not consider the impact of PhET simulation-based learning on influencing academic achievement and motivation in terms of gender. Also, to further understand the impact of PhET simulation-based learning, a study with a randomized sample from districts in Malawi can add sufficient literature in this area of study. The researchers also noted a need for studies on collaborative learning enhanced by PhET simulation-based learning on motivation and academic achievement. Lastly, a study on the impact of PhET simulation-based learning on cognitive engagement can substantiate the findings on academic achievement.

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Data Availability The data files that were used in data analysis for this research project are available from the corresponding author on reasonable request on google drive by following the link below: https://drive.google.com/drive/folders/1-9MLz9SKh-0LGj7119Yvwc3yVv8a6suT?usp=sharing.

Declarations

Ethical Statement The Directorate of Research and Innovation at the University of Rwanda-College of Education has reviewed and confirmed that this research adhered to ethical standards and principles.

Consent Statement Participating teachers gave informed consent. Students gave assent and parents permission for the use of their identifiable data.

Conflict of Interest The authors declare no competing interests.

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