Effect of interactive computer simulations on academic performance and learning motivation of Rwandan students in Atomic Physics

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ABSTRACT

Physics course is seen by both teachers and students as difficult when it comes to teaching and learning. Thus, there is a need to think of and integrate new and innovative ways of teaching which guarantee students an improved physics conceptual understanding. This study investigated the effect of interactive computer simulations on the academic performance and learning motivation of students. It used a quasi-experimental design with a quantitative approach. The participants were 163 senior five Rwandan students (80 students in a control group and 83 students in an experimental group). The investigation was done on students' learning in atomic physics using physics education technology (PhET) simulations for the experimental group and conventional teaching methods for the control group. An atomic physics achievement test as a pre/post-test and a questionnaire related to motivation were designed and examined for reliability and validity. Data were analyzed by means of descriptive and inferential statistics. On both test scores and learning motivation, the results show that the experimental group performed better than the control group with noticeable statistically significant differences. This research recommended that the integration of interactive computer simulations can be helpful in teaching and learning physics in Rwanda and future research may focus on the effectiveness of these simulations in the teaching and learning of other science disciplines like Chemistry and Biology.

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1. INTRODUCTION

An innovative way of teaching physics allows senior secondary students to become competitive as it provides them with the necessary skills to afford various career pathways in engineering and other professional domains. However, physics course is seen by both teachers and students as difficult when it comes to teaching and learning [1]. This perception originates primarily from the fact that physics needs mathematics as the logic and the language to communicate quantitative and qualitative aspects while dealing with physical phenomena [2]. Besides this, by its nature, physics is dominantly related to problem-solving and considered by many as an abstract subject which also contributes to the complexity level faced by students while learning. Lack of adequate teaching materials and qualified teachers, traditional teaching methods, and students' naive epistemological beliefs and misconceptions are also considered major factors inhibiting the betterment of physics education [3].

Furthermore, secondary schools, especially those in developing countries including Rwanda, suffer the shortage of laboratory equipment needed for students to explore various scientific activities, deepen conceptual understanding, and get acquainted with hands-on skills as the main elements of the intended competencies from physics learning. In Rwanda, only 21.6% of secondary schools are equipped with laboratories [4] and obviously, this is a small percentage which combined with the lack of improvisation skills on the side of teachers [5] results in a significant and persistent failure of high school students in sciences (physics included). The 3rd international mathematics and science study (TIMSS) of 1999 has confirmed this status of low students' performance in sciences and more specifically it has emphasized the prevailing problem in physics education worldwide. Based on previous study, in Rwandan secondary schools, both physics teachers and students do not have the cognitive and practical skills required in teaching and learning physics [6]. The same study has shown that Rwanda's secondary school physics teachers still rely on the use of traditional (teacher-centered) teaching approaches which train students to rote memorize the content for the sake of scoring marks but constrain them to remain short of conceptual understanding of the physics ideas. Despite various pieces of training that were offered to Rwandan secondary schools' physics teachers, physics teaching improvement is not yet realized [7]. The majority of students in Rwanda have negative attitudes towards Physics and they consider it as a subject that consists of a set of formulas and facts to be memorized [8]. Students with negative attitudes are more reluctant and their academic achievement is usually poor [9]. The academic failures result in a low level of student enrolment in science combinations as it has been argued by the Rwanda Education Board (REB) [10], despite heavy investment and much effort that was made by the Rwandan Government, some secondary schools with science combinations and more particularly with physics subject are to close because there are no students.

Despite all these critical issues, many things were and are still being done in order to improve science (especially physics) education. Among other things, presently, technology is upscaling its level of integration in the teaching and learning process. It has been integrated into classrooms whereby animations and interactive simulations serve as alternative ways of experimentation and demonstration. One class of these interactive computer simulations in physics education technology (PhET) simulations. PhET simulations are operationally interactive simulation software that was developed by a team of physics education researchers from the University of Colorado, based on the findings from the series of research on how physics students learn different physics topics and types of conceptual difficulties and misconceptions they encounter. PhET simulations were designed in such a way that, once properly used, they may ensure improved learning, increased student engagement, and improved beliefs towards physics teaching and learning approaches. PhET simulations have got worldwide acceptance as a result of how simple they are for their use, their versatility, and their online free availability [11].

While using PhET simulations, students get engaged and motivated due to some important PhET simulations' characteristics among others, a user-controlled dynamic visual environment, built-in challenges that are neither too hard nor too easy to be dealt with, and enough visual complexity embedded to create and maintain curiosity [12]. The majority of students who used PhET simulations for class activities, whether assisted by teachers or not, reported that working with simulations is more fun than real equipment and it is much easier to observe, explore, interpret and understand what happens with them [11]. The proper use of PhET simulations adds value to the academic success of physics students [13]. PhET simulations provide physics students and teachers with animated, interactive, and game-like environments which are motivating and intellectually engaging. PhET simulations also present the capacity to reduce cognitive load and enhance learning enjoyment. In the views of pre-service teachers, PhET simulations have the required capacity to change physics teaching and learning into easy and enjoyable activities [14].

These simulations are seen as possible powerful tools for physics teaching and learning, but they are relatively new in Rwanda and as a matter of fact, there is no research-based literature that may inform education sector actors (physics teachers and physics curriculum developers) on what might be the effect of using PhET simulations on academic performance of students. It is, therefore, in this context that researchers got an interest and curiosity to conduct this research across Rwandan Physics secondary schools.

The study focused on the use of computer simulations in learning and teaching physics to enhance students' academic performance. With the main objective of investigating the use of interactive computer simulations in teaching physics on students' academic performance and learning motivation, the comparison of student's test scores and level of motivation in learning physics has been made between students taught using PhET simulations and students taught using the traditional way. This study was guided by two main research questions: i) How does the use of computer simulations affect the academic performance of senior five Rwandan physics students in atomic physics?; ii) How is senior five Rwandan students' motivation toward atomic physics learning affected by the use of computer-simulated teaching tools?

2. RESEARCH METHOD

After identifying the existing problem, researchers started devising different mechanisms and ways to systematically solve it. This systematic way of solving a problem is generally termed research methodology. Research methodology always focuses on studying how research can be done scientifically.

2.1. Research paradigm and research design

During this research, a post-positivist research paradigm was employed to guide the research process. This research paradigm suits more to this research more because it allows the researcher to combine aspects of both positivism and interpretivism. As a research design, a quasi-experimental nonequivalent group design was used in this study. In fact, the senior five classes that were used during this research as control and experimental groups were not formed by students who were assigned to them randomly for the purpose of the research. Rather, these are classes that were formed by the school administration for the purpose of effective management of school activities. By the time of their formation, there was no intention to use them for this kind of research and therefore there should be a high probability that these groups are not hundred percent equivalent as they were not assigned to these groups randomly.

2.2. Research participants

The population of the study was all students that registered to study physics in senior five across all secondary schools in the Eastern Province of Rwanda through a multistage sampling technique. A sample of 163 senior five physics students (80 students in the control group and 83 students in experimental group) was considered for the research. This sample was taken from the Rwamagana, Kayonza, Ngoma, and Kirehe Districts of Eastern Province, Rwanda. Of this sample, 80 (49.1%) were males and 83 (50.9%) were females. Out of 80 students who were in the control group, 44 (55%) were males and 36 (45%) were females, while out of 83 students who were in the experimental group, 36 (43.4%) were males and 47 (56.6%) were females.

2.3. Data collection

During data collection, quantitative data were collected. In order to achieve this, different methods and tools were used, each of them having its importance. For quantitative measures relating to students' motivation, a Likert-scale questionnaire was used. Regarding this questionnaire, four factors reduced instructional material motivational survey (RIMMS) that was developed by Keller was adopted and adapted for this research. This questionnaire is composed of main four factors that demonstrate motivation and those are attention, relevance, confidence, and satisfaction which all together give ARCS as an abbreviation [15]. Each factor is composed of 3 items, meaning that the whole questionnaire was composed of 12 items and each item was answered to a 5-scale arranged as strongly disagree (1), disagree (2), undecided (3), agree (4), and strongly agree (5).

As the teaching and learning process aims to initiate a conceptual understanding change in the minds of students, atomic physics conceptual understanding questions were prepared in pre-test and post-test form for quantitative measures relating to students' scores. Both pre-test and post-test were composed of 11 questions each and focused on atomic models (Rutherford's and Bohr's atomic models), photoelectric effect, and Compton effect as aspects of atomic physics taught in senior five Physics majors as per Rwandan secondary school Physics Curriculum. For both pre-test and post-test were composed of five questions from atomic models, four questions from the Photoelectric effect, and two questions from the Compton effect.

In order to ensure the criteria of validity, different mechanisms were employed. While developing the atomic physics conceptual understanding test, the researcher has borne in mind the learning objectives of the atomic physics topic as set in the curriculum by REB. The researcher used a table of specifications while developing test items and prepared an assessment rubric for those tests. A checklist for test validity has been prepared. The Likert questionnaire was developed to collect data relating to students' motivation, atomic physics conceptual understanding test, and its assessment rubric and checklist were then all submitted to subject experts (physics lecturers from UR-CE and a randomly selected secondary school physics teachers for senior five), so that they further check aspects relating to various types of validity. The subject teaching experts' comments improved the validity (content, face and construct forms of validity). The reliability of the tools was checked by calculating Cronbach's Alpha Coefficient which was found to be $\alpha = 0.797$ for the pre-test and $\alpha = 0.752$ for the post-test. Relating to the Likert scale questionnaire to collect data associated with students' motivation, Cronbach's Alpha Coefficient value of reliability was $\alpha = 0.881$.

2.4. Data analysis

After data collection for six weeks, data were analyzed by means of descriptive and inferential statistics using the statistics package for social studies (SPSS). Descriptive statistics was employed while finding means, modes, and standard deviation (SD) from the data set. The inferential statistics (independent samples *t*-test) was employed in examining the significance of the difference between the means of both control and experimental groups. In order to understand the magnitude of the effect that resulted from the teaching intervention, Cohen's *d* value and Hake's learning gain factor were calculated and interpreted as (1).

$$Effect\ size = Cohen's\ d = \frac{M2-M1}{SD_{pooled}} \quad (1)$$

Where, *M2* is the mean score of the experimental group in the post-test and *M1* is the mean score of the control group in the post-test. SD1 is the standard deviation of the control group and SD2 is the standard deviation for the experimental group. As per Cohen, this formula is valid for independent samples t-test when two groups have almost the same size [16]. Hake's learning gain factor is mathematically calculated as (3).

$$SD_{pooled} = Pooled\ standard\ deviation\ for\ both\ groups = \sqrt{\frac{(SD1)^2+(SD2)^2}{2}} \quad (2)$$

$$< g > = \frac{(average\ scores\ from\ post\ test)-(average\ scores\ from\ pretest)}{(maximum\ scores\ for\ a\ test)-(average\ scores\ from\ pretest)} \quad (3)$$

3. RESULTS AND DISCUSSION

Before starting the research intervention, the researchers conducted a pre-test on all students from both experimental and control groups. The pre-test was done in order to compare students' initial state in terms of pre-existing knowledge of atomic physics concepts. Results from independent samples t-test are shown in Table 1 and they show a non-significant difference, t(161)=0.228; p=0.82, between control and experimental mean scores.

The obtained results from the pre-test for both control and experimental groups as in Table 1 show an overall average of 2.7 out of 11 marks. This average shows the poor academic performance of students from both groups in atomic physics. This poor performance is justified by the reason that before the intervention, atomic physics was a new topic to all students since there was no such or similar topic that they had learned before. However, this average has shown to both the researchers and the teachers that students from both groups knew something about atomic physics and it has helped teachers to prepare lessons considering the prior knowledge of students on the topic. It has informed teachers that they should not consider their students as empty vessels (tabula rasa) in atomic physics during class sessions but rather, they should consider the pre-existing knowledge possessed by students. It may be noted that these students have got some knowledge about atomic structure since they had learned some introductory atomic concepts in their ordinary-level chemistry course. A comparison of the academic performance of students from both control and experimental groups in the pre-test shows that the average was 2.78 out of 11 marks for the control group and 2.73 for the experimental group. An independent samples t-test showed that the difference between the pre-test mean scores of students from both control and experimental groups was not significant ($t_{(161)}$=0.228; p=0.82>0.05). The non-significance of the difference in the pre-test mean scores confirms that students from control and experimental groups were, academically, at the same level before intervention.

Table 1. Results from the pre-test scores of both groups

Group	N	Mean	OM	MD	SD	t	df	Sig.
Control	80	2.78	2.7	0.05	1.232	0.228	161	0.820
Experimental	83	2.73			1.001			

Note: Statistically significant at (p<0.05), MD=mean difference; OM=overall mean

3.1. Effect of interactive computer simulations on students' test scores

The first research question was investigating whether students' test scores were influenced by the use of computer simulations in teaching atomic physics. Table 2 shows the results of the independent samples t-test for post-test scores of students from control and experimental groups. The results show a significant difference, t(161)=-10.472; p=0.000, between post-test mean scores of experimental and control groups, and the corresponding effect size (Cohen's $d = 1.6$) is found to be larger. Results from the post-test for both groups, as presented in Table 2, show an overall mean score of 7.1 out of 11 marks. This mean score, when compared to the overall pre-test mean score of 2.7, shows a good academic improvement for all students after the intervention. A comparison of post-test mean scores of control and experimental groups shows that the mean score for students in the control group is 5.77 out of 11 marks while 8.39 for students in the experimental group. From these mean scores, both teaching approaches have though unequally, contributed to the academic achievement of the students. The teacher-centered approach has helped students in the control group to improve their performance from a mean score of 2.7 to 5.77 out of 11 marks while a learner-centered approach helped students in the experimental group to improve from 2.73 to 8.39.

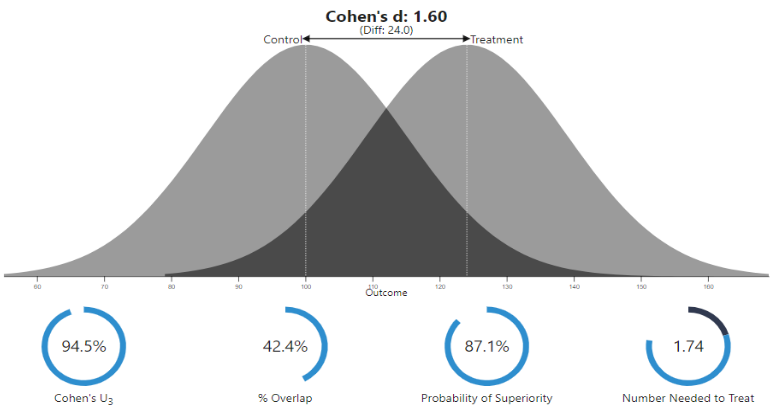
Table 2. Results from the post-test scores of both groups

Group	N	Mean	Overall mean	Mean difference	SD	t	Df	Sig	Cohen's d
Control	80	5.77	7.1	2.62	1.567	-10.472	161	0.000	1.6
Experimental	83	8.39			1.614				

Note: Statistically significant at ($p<0.05$)

Though it is obvious that both teaching interventions have worked for students, our interest was to find out which intervention has statistically worked better than another. To find out which intervention has worked, better an independent samples t-test was used. As shown in Table 2, the difference between post-test mean scores of students in experimental and control groups was found to be statistically significant, $t(161)=-10.472$; $p=0.00$. This statistical significance of the difference between experimental and control groups has shown that there is an effect on senior five physics students' test scores in atomic physics due to the use of computer-simulated teaching tools. Based on the findings of this research, senior five physics students' test scores in atomic physics were influenced by the computer-simulated teaching tools.

The size of the influence of computer-simulated teaching tools (PhET) has been quantified by means of effect size. All Figures which represent the effect sizes have been auto-generated by means of Kristoffer Magnusson's application for Cohen's *d* interpretation available online at https://rpsychologist.com/cohend/. A large effect size (1.6) was obtained which shows that students in the experimental group were 1.6 standard deviations above those of the control group as far as test scores were concerned. As shown by Gaussian densities distribution in Figure 1, 94.9% of students in the experimental group had scored above the average of those in the control group (Cohen's U_3) and 87.7% of the chance was that the students in the experimental group were above those of control group in terms of atomic physics test scores after the intervention (probability of superiority). There were 41.2% of all students have got similar scores irrespective of applied intervention (% of overlap).



Note:
The left side normal curve represents the control group while the right side represents the experimental group.

Figure 1. Gaussian densities for 1.6 Cohen's *d* value

The Hake's learning gain factor <*g*> was obtained to be equal to 0.37 for the control group and 0.67 for the experimental group. According to Hake [17], interpretation of <*g*>, the former is a little above the low gain, while the latter is almost close to the high gain, and therefore, there is a significant difference in the effect of both approaches. The learning gain factor for the experimental group is 1.86 times that for the control group. This means that, after the intervention, the gain in the level of conceptual understanding of atomic physics for Rwandan students in the experimental group was about 1.9 times when compared to the conceptual understanding level developed by students from the control group.

These results for the first research question agree with many of the findings from previous research. Radnai *et al.* [18] argued that when computer simulations are used in teaching and learning physics, students easily understand the physics concepts. Using their study on the use of PhET simulations in teaching simple electric circuits, Finkelstein *et al.* [19] found that the students taught with computer simulations perform better on conceptual understanding questions and they easily improve their skills in manipulating real equipment. They further found out that a student taught through manipulation and exploration of simulations learns considerably bigger content with a better mastery than those exposed to real equipment. Junglas [20] found that the academic success of students in thermodynamics increased by using computer-assisted instruction in science and physics teaching and learning activities. Kroothkaew and Srisawasdi [21] investigated the efficacy of computer-based simulation on students' achievement in physics and concluded that the use of computer-based simulation in learning physics enhances the achievement of the students.

3.2. Effect of interactive computer simulations on students' learning motivation

The second research question aimed at finding out whether the use of computer simulations in the teaching of atomic physics influences students' physics learning motivation. After running an independent samples t-test, a statistically significant difference between mean scores of experimental and control groups was obtained, t(161)=-5.051; p=0.000 as shown in Table 3. A medium effect size (Cohen's d = 0.8) was calculated. The significant difference between the means for both groups confirms that senior five students' motivation toward atomic physics learning was affected by the use of computer-simulated teaching tools.

Table 3. Results for motivation of students in both groups

Group	N	Mean	Mean difference	SD	t	Df	Sig.	Cohen's d
Control	80	4.01	0.51	0.584	-5.051	161	0.000	0.8
Experimental	83	4.52		0.687				

Note: Statistically significant at (p<0.05)

As shown in Figure 2, relevance and confidence as two dimensions of motivation were not greatly affected by the use of computer simulation in teaching atomic physics. However, attention and satisfaction were significantly affected since the difference between both groups vis-à-vis these two dimensions is considerably wide. It is therefore observed that while using simulations in learning atomic physics, students from the experimental group were more attentive and satisfied than those in the control group.

The quantification of how much the motivation of students was affected by the computer-simulated teaching tools was realized through the calculation of effect size or Cohen's *d*. After calculations, a medium effect size of 0.8 was obtained. With this effect size, as shown in Figure 3, it is understood that 78.8% of students in the experimental group, when learning atomic physics, were motivated to a level which is above the average motivation of students in the control group (Cohen's U_3). It is also seen from the effect size that a 71.4% chance is that students from the experimental group were highly motivated while learning atomic physics more than their counterparts from the control group (probability of superiority).

These results related to students' motivation are consistent with the findings from previous studies. For example, Hermann and Fuhrmann [22] argued that while using PhET simulations, students get engaged and motivated due to some important PhET simulations' characteristics among others a user-controlled dynamic visual environment, built-in challenges that are neither too hard nor too easy to be dealt with and enough visual complexity embedded to create and maintain curiosity. The proper use of PhET simulation adds value to the academic success of physics students and helps them to overcome fear and anxiety towards physics lessons and boosts students' interest and motivation to learn physics [23]. According to the researchers [24]–[27], the use of educational technologies, simulations included, creates a learner-centered environment that boosts students' inquiry-based problem-solving skills and improves students' learning motivation and academic performance. Findings of previous studies [28]–[30] suggested that simulations provide a significant impact on knowledge and inquiry skills acquisition.

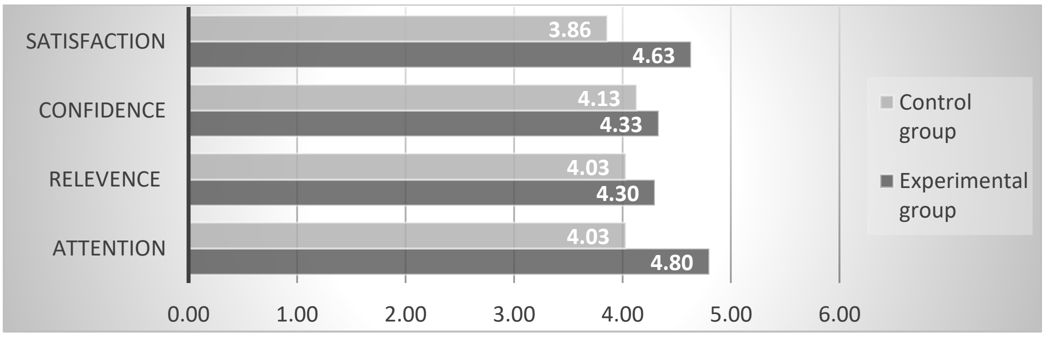
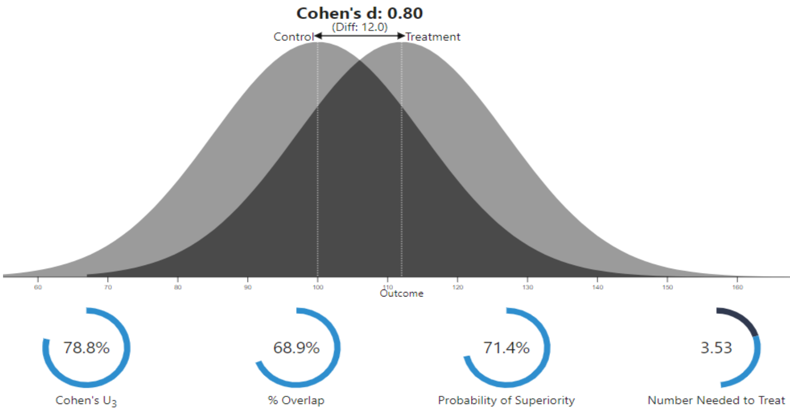


Figure 2. Comparison of students in control and experimental groups as per each dimension of motivation



Note:
The left side normal curve represents the control group while the right side represents the experimental group.

Figure 3. Gaussian densities distribution for 0.8 Cohen's *d*

4. CONCLUSION

In Rwanda's secondary school competency-based curriculum, learner-centered teaching approaches are suggested for the teaching and learning process since it ensures improved students' academic performance. From this research, it has been confirmed that the use of computer simulations (PhET) in the teaching of atomic physics has the potential to increase students' academic performance. During this research, the difference between post-test mean scores of students in experimental and control groups was found to be statistically significant and, for students' motivation in learning atomic physics, the experimental group was significantly more motivated than the control group. The high normal learning gain factor (Hake factor) for the experimental group compared to that for the control group also confirms it. Based on the findings of this research, we concluded that the use of computer simulations by students in learning atomic physics has a positive effect on their academic performance and learning motivation and hence may be adopted in physics classes in Rwandan schools. Future research may focus on the study of the effectiveness of the simulations in learning and teaching other science disciplines like Chemistry and Biology.

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