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Assessing the impact of multimedia application on student conceptual understanding in Quantum Physics at the Rwanda College of Education

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Abstract
Students ability to build correct knowledge relies on their understanding of concepts. Students must understand the concept well before applying it in real-life situations. With the advent of technology, teaching and learning quantum physics has been made easier and more effective in enhancing students' critical thinking and conceptual understanding. A multimedia-based learning approach is one way to enhance conceptual understanding. With the help of the multimedia application, this study aims to assess its impact on students' conceptual understanding of quantum physics at the University of Rwanda College of Education (UR-CE). The study adopted a quasi-experimental pre-test–post-test design with control and treatment group. Three hundred eighty-five undergraduate students in the UR-CE were purposively selected and allocated into the treatment group (193 students) and the control group (192 students). Control group students were taught eight quantum physics topics for six weeks using the traditional teaching approach, while treatment group students were taught the same topics using animations, PhET simulations, and YouTube videos. The study resulted in a very high statistically significant difference ($p < .001$) between teaching interventions provided after post-testing in favor of students who learned with multimedia (with a large effect size of 0.694). The use of multimedia resulted in a statistically significant increase in the student's conceptual understanding of quantum physics. The study's findings suggest that multimedia tools are effective for learning because they can enhance students' conceptual understanding of quantum physics. However, interactions between teachers and students or student-to-student are essential to facilitate conceptual learning and help the students gain a valuable understanding of their learning.

Extended author information available on the last page of the article

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Keywords Traditional teaching · Multimedia application · Quantum Physics · Student conceptual understanding · Higher learning

1 Introduction

Quantum physics (QP) proves to be a special area in physics teaching because of its abstract formalism, the differences from classical physics, the nearly complete absence of real experiments suitable for school, and the strong traditions in teaching partly due to the long unclear history of interpretation (Henriksen et al., 2014). Since it pertains to both the microscopic and macroscopic worlds, quantum theory is a collection of the simplest laws of nature. In quantum theory, atoms, nuclei, and elementary particles exhibit specific behaviors and interactions. Some concepts that describe QP phenomena, such as probability, uncertainty, or the wave function, are often too abstract for students (Stadermann et al., 2019). Students find it difficult to associate QP behavior with daily life experiences and physical reality (Henriksen et al., 2014; Krijtenburg-Lewerissa et al., 2017). Students study this course only as a compulsory course in the curriculum to be completed. QP education is a subject area that has recently attracted little pedagogical research, and university teachers must explore ways to teach it effectively in the classroom. Compared to other physics education studies, Kizilcik & Yavas (2016) found fewer studies on students' difficulties understanding QP content. Recent years have, however, seen a rise in studies of this nature (Gunawan et al., 2019). These studies are important parts related to the uncertainty principle (Akarsu, 2010; Ayene et al., 2011; Johansson & Milstead, 2008).

Learning advanced physics involves a tremendous amount of math sophistication and building on the knowledge one has acquired at the introductory and intermediate levels. University students perceive QP as a complicated concept to study; however, it must be taken to fulfill the requirements for their degrees (Mason & Singh, 2010). Pre-service teachers must master the basics of QP, which includes mathematical equations and abstract and difficult concepts, and be prepared to teach it to secondary school students. Unfortunately, university lectures on QP do not develop the ability of pre-service teachers to transfer their knowledge to the classroom (Nyirahabimana et al., 2022b). Training pre-service teachers effectively is a paramount duty to improve future education. These teachers should be well-equipped before they start their teaching careers.

The study conducted at UR-CE on prime indicators of current teaching methodologies and students' perceptions in Quantum physics show that the current teaching practices may not provide a holistic understanding of QP concepts and principles to pre-service physics teachers (Nyirahabimana et al., 2022b). However, it indicated that multimedia applications can be an effective tool to improving the teaching and learning of QP concepts. Therefore, introducing multimedia applications into teaching and learning QP in Rwanda could intervene with the conventional chalkboard approach. From all the observations, discussions with different educators, and reviewing articles, more investigation is needed to understand the impact of the multimedia technology application on students' conceptual understanding of QP at UR-CE. To achieve the goal of the present study, the following research question was considered: *To what extent do multimedia technologies improve physics pre-service teachers' conceptual understanding of quantum physics at the University of Rwanda?*

2 Problem background

In recent years, several secondary school curricula for instance, in Europe or in the USA as well as in Rwanda, have incorporated QP concepts due to their crucial role in the development of modern technology (Krijtenburg-Lewerissa et al., 2017). Furthermore, it is currently included in all introductory university physics courses worldwide (Greca & Freire, 2003; McKagan et al., 2009; Oh, 2011; Özcan et al., 2013; Scotti di Uccio et al., 2019).

Several studies (Wattanakasiwich, 2005; Lin & Singh, 2010; Krijtenburg-Lewerissa et al., 2017) have documented QP learning in secondary school. Few people have chosen the direction of higher learning institutions (Cataloglu & Robinett, 2002; Mason & Singh, 2010). Since implementing a competence-based curriculum in Rwanda, none of the studies focused on improving students' conceptual understanding in QP for university pre-service teachers who will teach this course afterward.

In the past, students viewed QP as an abstract subject unrelated to daily life, and they only took this course because it was required for graduation (Matjanov, 2021). The study conducted by Bouchée et al. (2022) on Towards a better understanding of conceptual difficulties in QP courses show that the abstract nature of QP is frequently found to be at the origin of students' conceptual difficulties. This is because in the traditional teaching of QP, the main motive of teachers is to prepare students for exams than coach them and make them understand the concept and syllabus topics. In this context, the current teaching approach used at UR-CE provides fewer opportunities for students to develop their understanding of QP concepts concepts (Nyirahabimana et al., 2022b).

Bouchée suggested the use of digital materials and discussing the history and philosophy of QP as teaching strategies to address students' conceptual challenges (Bouchée et al., 2022). Multimedia elements like videos, animations, and simulations can help teachers to illustrate abstract concepts and demonstrate complex concepts and principles in an easy-to-understand and easily-remember way (Bungum et al., 2018). This especially can be important in teaching and learning QP at UR-CE since many students consider it a difficult course (Nyirahabimana et al., 2022b).

The importance of interactive multimedia in enhancing teaching and learning physics is well-known worldwide. However, very few studies critically evaluated students' perceptions toward these multimedia in terms of their importance, acceptability, and suitability to enhance students' understanding (Bennett & Brennan, 1996). According to Mason & Singh (2010), the teaching and learning of QP, in particular, as well as other science subjects, can be enhanced by using multimedia methods such as demonstrations, simulations, animations, videos, and other applets. However, using animations, PhET simulations, and YouTube videos combined to improve student conceptual understanding in QP, particularly in Rwanda's higher education institution, has not been the subject of any research. All those issues discussed above make the magnitude of the study important for improving pre-service teachers' conceptual understanding in QP at UR-CE.

3 Literature review

3.1 Pre-service physics teachers' conceptual understanding of quantum physics

Students generally have misconceptions about QP since it is a challenging subject to understand. The conceptual understanding of QP among students has been studied (Akarsu et al., 2011; Mannila et al., 2001; Şen, 2002a, 2002b). A study by Kızılcık et al. (2016) on re-service Physics Teachers' Opinions about the Difficulties in Understanding Introductory QP Topics shows that transitioning from classical to QP was the most difficult for pre-service teachers. The authors confirm that this is particularly evident in QP topics that require a different understanding, like blacbody radiation, wave-particle structure of light, and the uncertainty principle. Participants from the same study emphasized that using visualizations, animations, experiments, and similar methods produced beneficial outcomes and facilitated understanding of the subject. Another study investigation on college students' conceptual understanding of QP topics was conducted by (Akarsu et al., 2011). The students in the study expressed that they repeated the QP course and found it difficult to understand its concepts. Similar results were observed in a study conducted in Rwanda (Nyirahabimana et al., 2022b).

3.2 The teaching and learning of quantum physics

The teaching of QP has not changed much since it was invented in the early twentieth century, and many students traditionally find it very abstract and challenging (Jian-hua & Hong, 2012; Wattanakasiwich, 2005). This means that the problem of the appropriate fitting of QP content knowledge is still unresolved. According to Wuttiprom, one of the critical challenges in QP is to find a way to introduce its concepts, as quantum theory is both technically and theoretically subtle, while most QP concepts are derived from theories and complex mathematical problems (Wuttiprom et al., 2009). Therefore, it is difficult for students to quickly understand the concepts and mathematical formulas (Susac et al., 2018). Furthermore, QP may be particularly challenging since the paradigms differ from general physics (Kızılcık & Yavaş, 2016). Questions like matter and radiation can be viewed as having a dual (wave-particle) nature. What are electrons like? Are they like particles or waves? Are they like both particles and waves, or like neither? These questions illustrate the psychological difficulties students are confronted with when trying to incorporate the concepts of QP into their overall conceptual framework (Donou-Adonsou, 2019).

Aside from students' difficulties in learning QP, Sadaghiani (2005) and Nilüfer (Prabavathi & Nilufer, 2015) found that instructors faced difficulties in teaching the subject as the QP' concepts were complex. In fact, the traditional teaching practices used do not provide students with enough opportunities to grasp abstract concepts and models because it is difficult for students to relate these models to anything in the physical world (Madsen et al., 2015). Also, this teaching approach provides fewer opportunities for students to develop their understanding of QP concepts. Such was observed in teaching and learning QP in Rwanda's higher institutions (Nyirahabimana et al., 2022c). The 21st-century teaching styles demand teachers to be creative and original by fully using the available resources instead of using blackboards or the typical lecture methods, which are inadequate to teach QP-related concepts (Stadermann et al., 2019).

3.3 Miltimedia technologies in teaching and learning

Technology has become a powerful tool to help students understand physics more efficiently and thoroughly (Bungum et al., 2018). With the emergence of technology in education, it is important to integrate technology into the teaching and learning process to improve students' critical thinking, concept-building, and motivation (Lai & Bower, 2019). Akarsu (2010) argued that QP seems to be a difficult and uninterested subject to students; however, teaching by multimedia intervention is one important way that can be used to cultivate the interest of students in QP subject. Visualization tools such as animations, simulations, and other mediums provided by multimedia technology make the process of teaching and learning QP more interesting and effective (Zainuddin et al., 2019).

With the help of multimedia tools, students can develop a connection between physical, mathematical, and graphical representations of QP phenomena, which in turn allows them to connect mathematical formalism with physical reality. Computer simulations also allow students to focus on the underlying principles that govern the simulation's behavior because the complex mathematical calculations involved in QP are incorporated into the simulations (Rehn et al., 2013). Chen et al. (2021) states that multimedia technology could be an effective, advanced, and economical method of teaching QP at universities. Kohnle et al. (2015) carried out a study to understand multimedia resources for teaching QP in the classroom. The study's findings exhibited that using animations and simulations in classrooms improves the conceptual understanding of the subject.

A similar study was conducted in Rwanda by Rusanganwa (2013) and Ndihokubwayo et al. (2020) to understand multimedia learning and explore the classroom environment in understanding physics. The findings exhibit that multimedia learning significantly influences recalling the physics concepts taught in the classroom. Multimedia applications enhance understanding of physics concepts and enhance teaching physics efficiency in the classroom. This improved students' conceptual understanding of the subject content. Research studies show that multimedia applications enhances the teaching of QP through visuals, animations, simulations, videos, and graphs, resulting in active students' discussions, multimedia activities, and mastery of QP knowledge (Nyirahabimana et al., 2022a; Rudolph, 2017). While undergraduate courses for physics pre-service teachers play a critical role in their future career, little is known about their conceptual understanding specifically in QP. Still, there is a need to conduct a study with pre-service teachers on understanding QP concepts generated in standard research-based instruction tools such as the Quantum Physics Conceptual Survey (QPCS)(McKagan et al., 2010).

3.4 Theoretical framework

This study is directed by the cognitive Multimedia Learning Theory (Ibrahim, 2011) since multimedia in teaching physics was expected to enable lecturers to deliver the content differently to enhance students' learning. Cognitive learning develops students' thinking abilities through interacting with the environment and building on students' prior knowledge. Through this theory, human cognition interacts with oral and nonverbal contents and events since there is a referential connection linking verbal and nonverbal clues (Ibrahim, 2011). Knowledge is easily acquired and stored in memory when presented in different forms, such as verbal and visual representations (Wigham, 2012).

The cognitive theory of multimedia defines how learners construct knowledge using words, pictures, animations, simulations, videos, and audio (Bull, 2009). Cognitive learning is demonstrated by knowledge recall and intellectual skills like comprehending information, organizing ideas, and analyzing and synthesizing data. Therefore, this study tested three cognitive aspects of conceptual understanding: recall, comprehension, and analysis. A simple comparison of conceptual understanding of each cognitive aspect was conducted to understand the conceptual understanding of quantum physics between the traitment and control group students.

4 Research methodology

4.1 Research design

The study used a quasi-experimental pre-test–post-test design. The design is one the experimental design that, when properly used, tests better the cause-effect relationship (Fraenkel et al., 2012). In this study, the research design allowed administering a pre-test and post-test to both control and traitment groups to test the impact of multimedia technologies on students' conceptual understanding of QP. A pre-test allows the researchers to compare the two groups before the intervention. In contrast, a post-test allows the evaluation of the effectiveness of the traditional method and multimedia technique in teaching and learning a subject. Three hundred eighty-five students registered in the second year of the undergraduate program at the UR-CE in the Department of Mathematics, Science, and Physical Education during the academic year 2021–2022 from Mathematics-Physics-Education (MPE), Physics-Chemistry-Education (PCE), and Physics-Geography-Education (PGE) combinations were purposively selected and allocated into two groups (traitment-treatment and control). The treatment group had 193 students, and the control group had 192 students. The ages of participant students range from 21 to 25. In this study, treatment groups was used to indicate the students who studied in multimedia classes used multimedia instruction. Likewise, the control group refers to students that learned with a lecture or traditional instruction. In this study, QP or quantum mechanics (QM) are interchangeably used. Two physics Lecturers with the same academic background helped the respective groups (control and treatment) to understand the subject content. Before starting the teaching process, we administered the pre-test to all groups of students.

4.2 Treatment group

Students in the traitment group were taught different topics of QP (blackbody radiation, photoelectric effect, Compton Effect, wave aspects of particles, De Broglie's hypothesis, diffraction, interferences & double slits experiment, model of the atom, uncertainty relations, wave function & Schrodinger equations) topics for a period of six weeks using the multimedia (animations, PhET simulations, and YouTube videos). During this class, a concept was introduced by animation to engage students; then, before manupulating a simulation or playing a video, prediction questions were given to students to help them predict the outcomes of the experiment; then, the concept was explained by using their observations. The teaching took place in the normal academic timetable of the college. All animations, PhET simulations, and YouTube videos used during the intervention were selected by the researcher (first author) and the lecturer who agreed to teach the traitment group. The researcher conducted two days of training for this lecturer on how to use selected multimedia. During this training the main focus was on the four main steps of teaching practice in the design of multimedia application: (1) each introduction of the concept begins with a driving question, which is targeted to the alternative conceptions commonly found in students, followed by animation that illustrates the concept (2) simulated experiment with PhET simulation or YouTube video that challenge students' ontological and epistemological beliefs and help them reconstruct the scientific knowledge; (3) the same driving question is asked again (step-1), and student individuary or in group are required to provide an answer with explanations for what happens in the phenomenon, and (4) then lecturer assisting the students on how to draw a conclusion based on observations and evidence in order to reconstruct new knowledge. This active learning or interactions between teachers and students or student-to-student were very important in helping students to develop better conceptual learning of course concepts.

4.3 Control group

On the other hand, students in the control group were taught the same selected QP topics (blackbody radiation, photoelectric effect, Compton Effect, wave aspects of particles, de Broglie's hypothesis, diffraction, interferences & double slits experiment, model of the atom, uncertainty relations, wave function & Schrodinger equations) for six weeks using the traditional teaching approach (chalkboard) in the class. The lecturer explained the topics in this class without instructing students to watch any video or manipulate any simulation. After six weeks of teaching in both groups, the post-test was also given to all participants to examine if the multimedia intervention had some effects on students' conceptual understanding. However, to minimize the effects of this design that advantage participants of the treatment over participants of the control group, a remedial session was provided to students who underwent into traditional method after data collection. Thus, the control group was also given some sessions using multimedia applications as the treatment group did.

4.4 Motivation for experimental students

Considering the motivation of the experimental students is an important factor when evaluating the impact of new learning approaches such as multimedia applications. Motivation can play a significant role in student learning and academic performance. If students are highly motivated, they are more likely to engage with the learning material, participate actively in class, and persist in the face of challenges. Conversely, if students are not motivated, they may have difficulty paying attention, understanding the material, and retaining information. If there are differences in motivation levels between the two groups, this could potentially confound the results of the study. For example, if the treatment group had higher levels of motivation than the control group, any observed differences in conceptual understanding could be attributed to motivation rather than the use of multimedia applications. Therefore, it was important to control for motivation levels statistically by treating both groups in a similar way apart from the intervention delivered.

4.5 Instrument and pilot

From the literature, four conceptual surveys/tests related to quantum physics and quantum mechanics concepts were selected from PhysPort Assessments. These comprised Quantum Mechanics Formalism and Postulates Survey (QMFPS), Quantum Mechanics Survey (QMS), Quantum Physics Conceptual Survey (QPCS), and Quantum Mechanics Concept Assessment (QMCA). In order to validate the content of these tests, ten university professors (who teach modern physics, including quantum mechanics) were given them. Study participants were asked to select questions from provided tests related to QP content taught at UR-CE to assess students' conceptual understanding of the subject matter. Based on the validation report, one test was selected, Quantum Physics Conceptual Survey (QPCS)(McKagan et al., 2010), to cover 80% of the content for the QP module taught at UR-CE. To cover the 20% remaining, six questions from the module were added to the questions of QPCS, and then we came up with 36 items for the QPCS. The 36 items were again content validated by four university educators who teach quantum mechanics/physics. The QPCS items are freely available on physport.org, while added items are provided in Appendix 1.

At a stage of reliability, 30 students from different classes (not involved in the real study) were invited to take the test before implementing it to the target students. We piloted the test one month after the scheduled study started. On the part of students, there was a two-week interval between the pre and post-test. In each case, the test duration was one hour and 30 min. We used a test-retest method to check the reliability and got a low Pearson correlation coefficient (r = .280) and a medium internal consistency (Cronbach alpha a = 0.652). We then checked the reliability of items and found some items were invalid (the statistical significance to the total score was above the 0.05 alpha level). Thus, we removed questions 3, 19, 27, and 36 and got a high internal consistency (a = 0.718). Thus, from 36 questions, the pre-and post-tests consisted of the same 32 multiple-choice questions taken to the real study and analysis. This test was composed of questions that are categorized into three cognitive aspects (recall, comprehending, and analyzing).

4.6 Data analysis

Data from the pre-test and post-test of the control and treatment groups were analyzed using MS Excel 2016, where each chosen code for each question was recorded. The same software was used to analyze all data. The first utmost work was to organize and filter data by removing all students who missed either pre-test or post-test from control and treatment groups (20 students were removed). The total number of participants taken to the analysis phase was 178 for the control group and 187 for the treatment group. Descriptive statistics were calculated and presented in the table. These results were supplemented by inferential statistics by measuring the effect between tests and groups of intervention using the t-Test of paired and independent groups, respectively. The effect size of the mean scores was also measured using Cohen's effect size [d=(Post-test average score–Pre-test average score) / the square of standard deviation)]. The sum of correct answers was calculated for each student, and the percentage of students who answered each question correctly in the pre-test and post-test was calculated for the control and traitment groups.

5 Results and discussion

After exposing the control group to the traditional learning approach and the treatment group to the active learning that incorporated animations, PhET similations and Youtube video, the treatment group exhibited a better understanding in different concepts of QP than the control group. Table 1 presents descriptive statistics of both control and treatment groups before and after teaching intervention.

From the data above in Table 1, a very high statistically significant difference ($p < .001$) was found from pre-to post-test with a very large effect size (0.923). Likewise, a difference was found between teaching interventions provided after post-testing in favor of the treatment group (students learned with multimedia) with a large effect size (0.694). Specifically, we have computed inferential statistics between QP concepts to measure the effect of multimedia instruction versus the lecture approach. Table 2 displays the effect of multimedia instruction in teaching blackbody radiation (BBR) to control and treatment group students. There was a high statistically significant difference ($p < .01$) between teaching

Table 1 Descriptive statistics of both control and treatment groups before and after the teaching intervention

Groups of teaching intervention		Overall Pre-test		Overall Post-test	
		Statistic	Std. Error	Statistic	Std. Error
Control group	Mean	11.271	0.390	44.874	0.840
	Std. Deviation	5.200		11.213	
	Minimum	0.000		3.125	
	Maximum	21.875		59.375	
	Range	21.875		56.250	
Treatment group	Mean	11.514	0.388	73.596	0.816
	Std. Deviation	5.307		11.156	
	Minimum	0.000		46.875	
	Maximum	21.875		93.750	
	Range	21.875		46.875	

Table 2 Effect of multimedia instruction on teaching different concepts ofquantum physics

Concept	Control group		Treatment group	
	Pre-test	Post-test	Pre-test	Post-test
Black body radiation	21.49	59.27	27.01	75.94
Compton effect	30.90	65.17	30.48	74.87
Photo electric effect	0.18	47.75	0.35	72.37
Wave theory and particle theory	0.00	46.25	0.00	68.80
Wave particle duality	33.33	36.14	33.51	74.86
deBlogrie hypothesis	0.00	0.01	0.00	0.03
Double slit experiment	16.18	49.21	15.94	79.47
Uncertainty principle and wave packet	0.00	17.56	0.00	68.05
Total energy of particle and probability of finding a particle	0.00	13.06	0.00	77.54

BBR using multimedia instruction and lecture approach in favor of multimedia instruction (with a small effect size of 0.031).

However, the Compton effect (CE) did not show any effect of multimedia instruction in teaching and learning before and after being exposed to pre-and post-test. Thus, there was no statistically significant difference ($p > .05$) between teaching CE using multimedia instruction and the lecture approach (with a small effect size of 0.008).

There was a very high statistically significant difference ($p < .001$) between teaching photoelectric effect using multimedia instruction and lecture approach in favor of multimedia instruction (with a small effect size of 0.110).

There was a very high statistically significant difference ($p < .001$) between teaching wave theory and particle theory using multimedia instruction and lecture approach in favor of multimedia instruction (with a small effect size of 0.102).

There was a very high statistically significant difference ($p < .001$) between teaching wave-particle duality using multimedia instruction and lecture approach in favor of multimedia instruction (with a medium effect size of 0.255).

There was a very high statistically significant difference ($p < .001$) between teaching the de Blogrie Hypothesis concept using multimedia instruction and the lecture approach in favor of multimedia instruction (with a large effect size of 0.691). However, the overall performance was small as the mean of each group stayed very small.

There was a very high statistically significant difference ($p < .001$) between teaching double-slit experiments using multimedia instruction and lecture approach in favor of multimedia instruction (with a small effect size of 0.194).

While teaching these concepts the results show that there was a very high statistically significant difference ($p < .001$) between group taught uncertainty principle and wave packet using multimedia instruction and lecture approach (with a large effect size of 0.611).

There was a very high statistically significant difference ($p < .001$) between teaching a particle's total energy and the probability of finding a particle using multimedia instruction and lecture approach in favor of multimedia instruction (with a large effect size of 0.644).

The fact that Compton effect did not realize any significance may be depicted from a few questions in this concept. Several studies have shown a difference in concepts; however, the uniqueness of our study is that almost all concepts showed a positive significance toward the intervention under study. For instance, Uwamahoro et al. (2021) revealed a statistical significance in reflection/refraction and lens concepts due to PhET simulations and optical instruments due to YouTube videos. However, despite a modernized teaching intervention, the mirror concept needed to realize its significance. Likewise, apart from performance revealed by students' scores, the conceptual understanding was most increased in the treatment group compared to the control group. Nyirahabimana et al. (2022b) show that students show conceptual difficulties in some QP topics, this was taken into account when adapting QPCS. However, there were nine topics in which QPCS questions were asked, and percentages of students who performed each question were described. These topics include blackbody radiation (BBR), Compton effect (CE), Photoelectric effect (PEE), wave theory and particle theory (WTPT), wave-particle duality (WPD), de Broglie hypothesis (de Bloglie H), Double slit experiment (DSE), the uncertainty principle and wave packet (UP & WP), the total energy of a particle in a box and probability of finding a particle (TEP & PP). Figure 1 compares the number of students correctly answering each of the 32 test questions in both control and treatment groups before the teaching intervention.

From Fig. 1, most of the questions (24 out of 32 questions) have challenged students before learning the QM module, except eight questions (Q3 and Q4 in BBR, Q5 of CE, Q12 and Q14 in WPD, Q15 related to De Bloglie Hypothesis, and Q22 and Q23 in DSE) that have surpassed difficulty index of 30% of students correctly

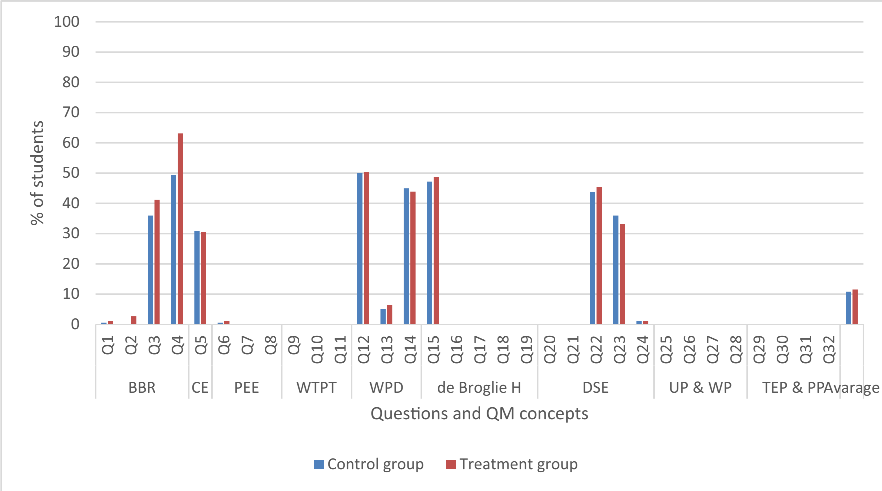


Fig. 1 Comparison between control and treatment groups before the intervention

answering these eight questions. The concepts of PEE, WTPT, UP & WP, and TEP & PP were most difficult for students before a teaching intervention occurred. The pre-test results show that students in both groups have shown the same low conceptual understanding of related quantum physics concepts. Therefore, this confirms the results of students' performance scores presented at the beginning of this section.

While seeking the % of students from both groups (control and an treatment group) who correctly answered each question in the post-test, general observations show a positive shift in both groups after learning QP as displayed in Fig. 2.

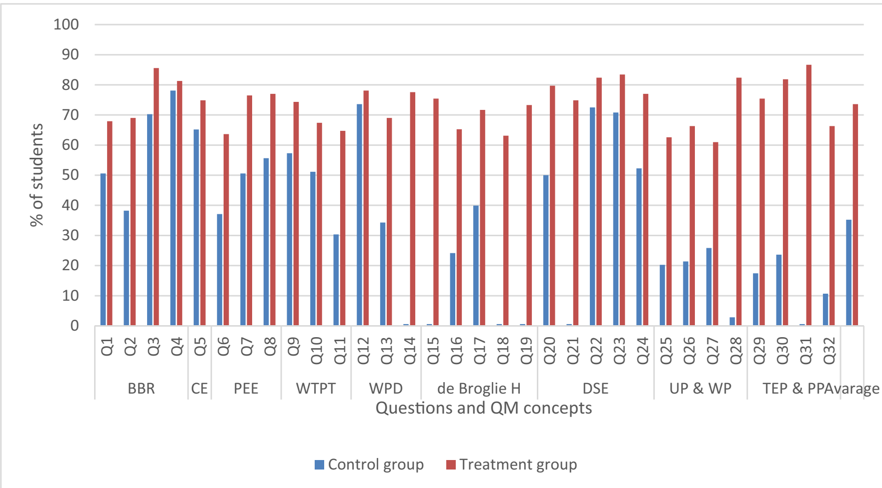


Fig. 2 Comparison between control and treatment groups after the Intervention

In the treatment group, all questions were answered correctly by more than 50% of students (with a percentage of students > 60% < 90%). These results were due to the use of multimedia instruction. However, the lecture method could not help many students to get the correct answers to most questions. For example, the control group performed poorly in Q14, Q15, Q18, Q19, Q21, Q28, and Q31.

Figure 2 shows that traditional teaching (lecture approach) used in the control group did not help to overcome students learning difficulties about wave-particle duality (Q14), De Bloglie Hypothesis (Q15, Q18, and Q19), double slit experiment (Q21), the uncertainty principle and wave packet (Q28), the total energy of the particle and probability of finding a particle (Q31), while multimedia applications used during the intervention for the treatment group (Animations, PhET simulations, or YouTube videos) supported students' conceptual understanding by connecting mathematical formalism to physical reality, by visualizing abstract and unobservable QP phenomena abovementioned.

Traditional teaching practices need to give students more opportunities to understand QP concepts more efficiently, as they could not answer basic conceptual questions related to this course after learning it. The results of the post-test in the treatment group showed that multimedia applications supported students' meaning-making by introducing them to the counterintuitive principles or results found in QP concepts, for instance, in the photoelectric effect, wave theory, particle theory, de Broglie hypothesis, the uncertainty principle, and wave packet, etc. Again, these findings confirmed that animations and video helped to visualize QP objects that are often "strange" and difficult to put into pictures, like wave functions and the probability amplitude of a particle. During the intervention, students in the treatment group were helped to understand these concepts by making representations of them when we teach and popularize them. We used video and animation to represent these quantum objects accurately. Also, by using simulations, concepts were discussed and exemplified in concrete terms. Therefore, from all the above findings, we can confirm that multimedia applications increased students' QP knowledge and recall of subject content compared to the traditional teaching method.

Such outperformance in the multimedia class took us to misconception remediation analysis. Before learning, almost all questions showed misconceptions in both groups, except five questions (Q4 in BBR, Q12 and Q14 in WPD, Q15 in de Bloglie H, and Q22 in DSE). Thus, many students could find a correct answer to only these five questions. After learning, in many treatment groups, students could select a correct answer to all questions (see Fig. 3).

However, students in the control group showed misconceptions since many provided alternative and wrong answers to many questions (18). Figure 4 displays these results. The questions that persisted difficulties were Q14 in WPD, Q15, Q18, and Q19 in de Bloglie H, Q21 in DSE, Q28 in UP & WP, and Q31 in TEP & PP. Mostly, Q14 and Q15 failed students in the post-test compared to the pre-test.

Q14 asked to choose the most appropriate answer from A through C. (A) The de Broglie wavelength of the particle will increase, (B) The de Broglie wavelength of the particle will decrease, and (C) The de Broglie wavelength of the particle will remain the same (Fig. 5) (McKagan et al., 2010).

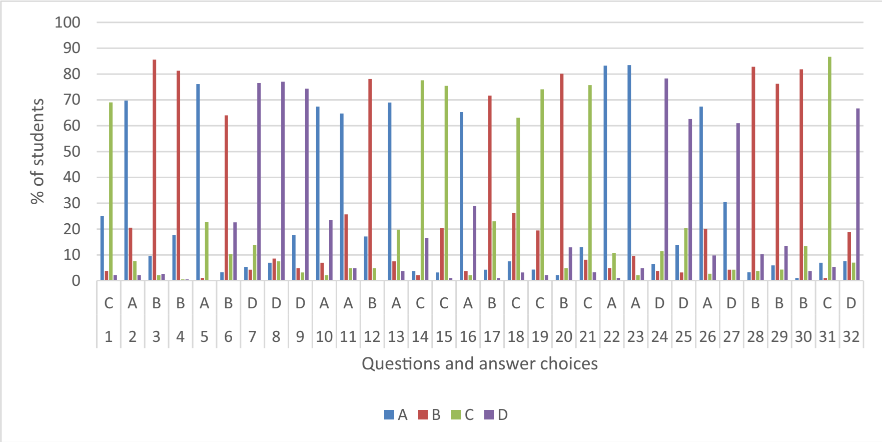


Fig. 3 Answer choices in the post-test of the treatment group

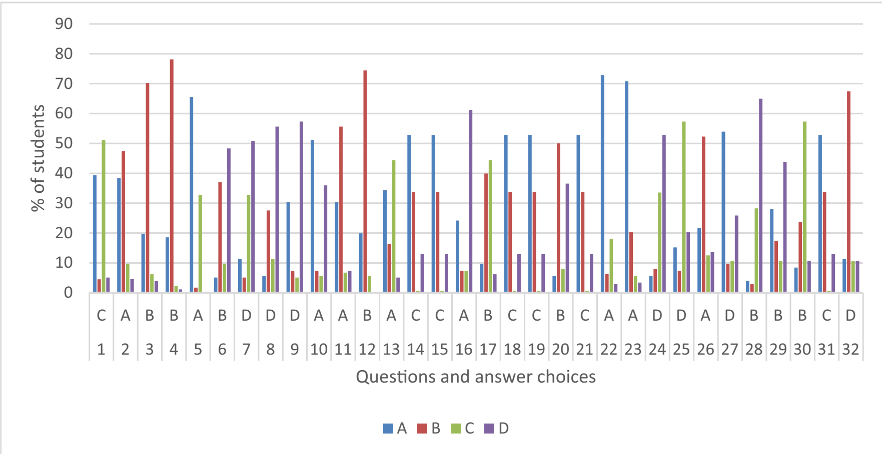
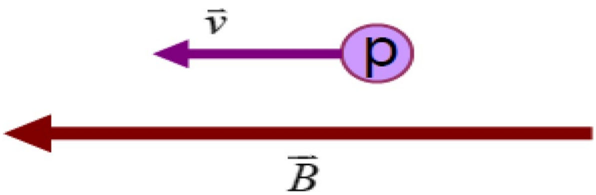


Fig. 4 Answer choices in the post-test of the control group

Fig. 5 Demonstration-related to question #14



What will happen when a positively charged particle moves through a magnetic field in the same direction as the field, and its velocity is therefore constant? The answer would be (C), but many students (53%) answered (A). Likewise, Q15 asked to choose the most appropriate answer from A through C. (A) The de Broglie wavelength of the particle will increase, (B) The de Broglie wavelength of the particle will decrease, and (C) The de Broglie wavelength of the particle will remain the same (Fig. 6) (McKagan et al., 2010).

What will happen when a quantum particle travels from left to right with constant total energy in a region where the potential energy is constant? The answer would be (C), but many students (53%) answered (A). This show how the students in the control group showed misconceptions after learning quantum physics.

Other studies have shown misconceptions in physics. For instance, the difficulties persisted even after the usual teaching practices among Rwandan undergraduate students. Similarly, teaching mechanical waves (Kanyesigye et al., 2022) and electromagnetic waves (Kanyesigye & Kemeza, 2021) in Ugandan secondary schools through problem-based learning instruction revealed some misconceptions still arise even after three months of intervention as traditional methods do. Thus, the uniqueness of the present study is that multimedia learning proved the extensive remediation of persisting alternative conceptions. Our intertwined study employed classroom observation protocol for undergraduate STEM, revealing a good atmosphere in multimedia class compared to lecture class (Nyirahabimana et al., 2022c). Students enjoyed learning, and such enjoyment may be contributed to the performance and conceptual understanding resulting in the present study. This was successfully followed by adopting a more learner-centered and technological approach, as students claimed before the teaching intervention (Nyirahabimana et al., 2022b).

Having a concept-based understanding means being able to relate concepts to everyday situations in our lives. Conceptual understanding refers to the ability to recall, comprehend, and analyze the information obtained. The use of multimedia applications improves students' ability to solve physics problems, develops inference skills in physics and logic, and enhances their creativity in verbal and figurative expression. Ndihokubwayo et al. (2021) demonstrate in their work that multimedia intervention can facilitate students better understand abstract physics concepts that are difficult for teachers to explain. Multimedia intervention can also increase students' motivation to learn quantum physics. The study analyzed

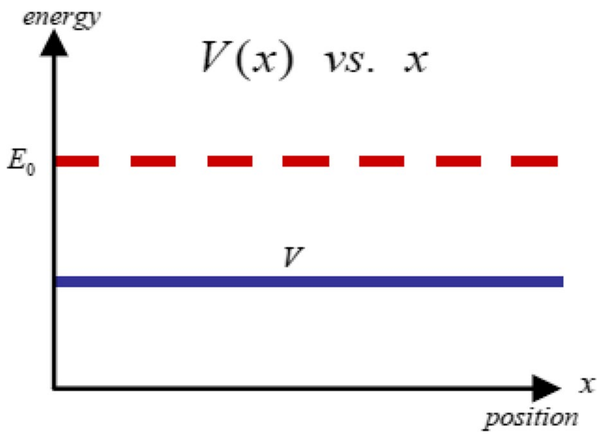


Fig. 6 Demonstration related to question #15

the students' conceptual understanding test results to determine the level of conceptual understanding the students achieved by counting the correct answers from each cognitive concept (recall, comprehending, and analyzing). The treatment group obtained 95.3% of correct answers for cognitive aspect recall, while the control group acquired 81.7% (see Fig. 7).

The findings exhibit that both groups correctly answered the questions in the recall category. There were no high-level thinking problems associated with the recall category. The recall category requires students to have a basic grasp of their memory to answer the questions correctly. The treatment group obtained 87.1% of correct answers for cognitive aspect comprehension, while the control group acquired 81.2%. Comprehending is a higher level of critical thinking compared to recalling, as it involves an individual ability to understand the concepts and remember them and think from different perspectives. The treatment group received 78.5% correct answers, while the control group received 59.8% correct answers in the cognitive aspects of analyzing. Analyzing requires students to break down their knowledge into its constituent parts and check how they are connected. The students must start and analyze on a higher level.

In order to ensure that students develop conceptual understanding and mastery of learning in science education, teachers are encouraged to use diverse methods in their teaching. Teachers should move toward the inclusion of active learning methods in the classroom. Moreover, teachers should strive to create a learning environment that allows the flourishing and thriving of modern teaching strategies to enhance the development of conceptual understanding to meet the needs and expectations of the competitive labor market. Student engagement and understanding of teaching materials are emphasized more in today's education over spoon-feeding the facts. The study's findings suggest that multimedia tools are effective for learning because they can enhance students' conceptual understanding of QP. Additionally, interactions between teachers and students or

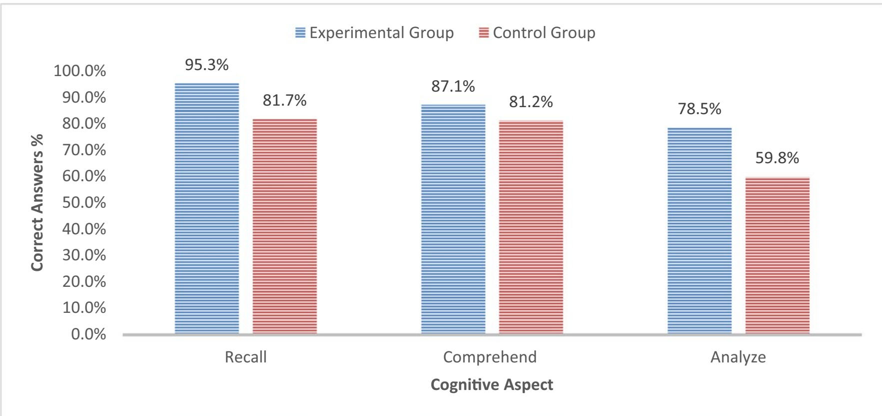


Fig. 7 Comparison between groups with respect to the cognitive aspect

student-to-student are important to facilitate conceptual learning. This will help the students gain a valuable understanding of their learning.

6 Conclusion

Students at the University of Rwanda College of Education were assessed for their conceptual understanding of quantum physics through multimedia applications. The study findings suggest that multimedia tools positively influence students' conceptual understanding. The treatment group found a higher conceptual understanding score than the control group. Students in the treatment group received a higher percentage of correct answers regarding recalling, comprehending, and analyzing cognitive aspects. In contrast, a lower percentage was achieved by students in the control group. Animations, PhET simulations, and YouTube videos were used as multimedia applications to increase students' conceptualization of QP. The study findings exhibit that multimedia applications positively enhance students' subject knowledge and conceptual understanding of QP. Multimedia application in the teaching process has made many innovative changes shifting the old traditional paradigm. The traditional teaching practice is not the best way to develop a deep conceptual understanding of physics concepts and QP principles. Using animations, PhET simulations, and YouTube videos helped improve the teaching process of QP. and increase students' conceptual understanding in QP.

7 Limitations and future work

This study focused on pre-service teachers from public higher-learning institutions. It did not study the situation of learning quantum physics for another category of students like secondary school students or private higher learning institutions. The study only focused on quantum physics. It did not look at other modules to ease the comparison of domains of physics taught to pre-service teachers. The study could be replicated in other areas of Physics like Mechanics, optics, and properties of matter. It is another area of Physics that pre-service teachers learn in Rwanda colleges of education. UR-CE should also sensitize lecturers to use ICT tools such as multimedia technologies not only in physics but in other science subjects. Further studies may look into effects brought by gender differences, school environment, students' motivation and attitudes, and teachers' appreciation of the use of multimedia applications in other physics-related courses.

Appendix 1

A: Suplimented items UR-CE module to QPCS

1. Which of the following is the characteristic of the black body?
   A. A perfect absorber but an imperfect radiator
   B. A perfect radiator but an imperfect absorber
   C. A perfect radiator but a perfect absorber
   D. A perfect conductor
2. A black T-shirt is a good model of a blackbody. However, it is not perfect. What prevents a black T-shirt from being considered a perfect blackbody?

A. The T-shirt reflects some light.
B. The T-shirt absorbs all incident light.
C. The T-shirt re-emits all the incident light.
D. The T-shirt does not reflect light.

3. Rayleigh-Jean's law holds good for which of the following?
   A. Shorter wavelength
   B. Longer wavelength
   C. High temperature
   D. High energy
4. The Compton effect can be explained on the basis of __________
   A. Wave nature of light
   B. Quantum theory of light
   C. Ray optics
   D. Wave optics

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Data availability The datasets generated during and/or analyzed during the current study are available to use from the Mendeley repository: Dataset from the University of Rwanda College of Education during Learning Quantum Physics. https://data.mendeley.com/datasets/gm49fmx86t/5.

Readers are able to view the raw data, replicate the study, and re-analyze and/or reuse the data (with appropriate attribution). The data has been published previously by the Digital Commons.

Declarations

Ethics approval The research project successfully passed through the University of Rwanda College of Education ethical committee by following the established ethical process: (1) presentation of the research proposal, (2) submission of the application and tools to be used for ethical research clearance, and (3) review and approval of the application by the ethical research committee.

Also, before participation, all participants were provided with clear and comprehensive information regarding the study's purpose, procedures, and benefits. They were given ample time to ask questions and clarify any concerns before providing their voluntary and informed consent to participate. Participants were assured of their right to withdraw from the study without penalty.

Conflict of interest All co-authors have seen and agree with the content of the manuscript, and there is no financial interest to report.

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