The Effectiveness of Digital Resources in Teaching Nuclear Physics in Secondary Schools in Morocco

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Manuscript received July 11, 2025; revised August 8, 2025; accepted September 28, 2025; published February 12, 2026

***Abstract*—This experimental study aims to evaluate the educational effectiveness of integrating interactive 3D animation into the teaching of nuclear physics at the secondary school level in Morocco. Conducted with 200 students in their final year of high school studying science (with a focus on physics), the research compares the cognitive gains, engagement, and attitudes of students between a control group receiving traditional instruction and an experimental group benefiting from a teaching scenario enriched by a 3D digital resource. Using a mixed methodology (pre-tests, post-tests, questionnaires, observation grids, statistical analyses), the results show a significant improvement in the performance of the experimental group, particularly in conceptual modeling, motivation, and autonomy. The study also highlights a shift in teaching practices towards more interactive approaches. These results underscore the relevance of using educational technologies to enhance equity, motivation, and learning effectiveness in complex and abstract disciplines such as nuclear physics.**

***Keywords*—3D animation, digital resources, nuclear physics, active learning, experimentation, qualifying secondary education**

I. Introduction

Educational aids and technologies are an essential part of the educational process and an integral part of the overall education system, which has prompted educational institutions around the world to adopt educational and communication technologies to achieve their goals and address the challenges facing the world today due to the rapid evolution of the information and communication revolution, so that the use of teaching aids has become a necessity in education. Due to the rapid evolution of the information and communication revolution, the use of teaching tools has become a necessity for education [1]. These tools can be used to create a diverse experience for learners, preparing them with a high level of competence that qualifies them to face the challenges of the modern era [2, 3]. Teaching nuclear physics at secondary school level is a major educational challenge due to the complexity and abstract nature of the concepts involved. Concepts such as the composition of the atomic nucleus, isotopes, types of radiation (α, β, γ) and fission and fusion reactions are invisible to the naked eye and difficult to grasp without appropriate visualization tools. Learners struggle to visualize these phenomena, which often leads to misconceptions, a superficial understanding of models, and a decline in motivation when faced with a subject that is perceived as theoretical and distant from their everyday reality [4].

In the Moroccan educational context, these obstacles are exacerbated by several structural constraints. School laboratories, where they exist, are often under-equipped, limiting the possibility of conducting experiments that illustrate nuclear phenomena. The teaching materials available in schools are generally limited to textbooks and static diagrams, which are insufficient to convey the dynamic and evolving nature of the processes being studied. Limited access to interactive digital tools or modern multimedia resources also hinders the implementation of innovative and engaging teaching approaches. In this context, the use of interactive 3D animations appears to be a relevant and appropriate educational solution. These tools enable visual modeling, in real time, of abstract phenomena such as radioactive decay, particle interactions, and nuclear transformations. By combining visual realism and interactivity, they promote conceptual understanding, stimulate learners' interest, and facilitate knowledge acquisition. Their integration into teaching practices could thus help to bridge the gap between the conceptual demands of nuclear physics and the educational resources currently available in the Moroccan education system [5]. Those who follow developments in educational programs in general, and physics and chemistry programs in particular, will note the strong presence of information and communication technologies in current curricula [6]. An inventory of the various applications mentioned in the 2007 edition of the subject's curriculum and teaching guidelines manual or in the prescribed textbooks shows the clear and obvious presence and strong entry of this technology as an essential component of our teaching programs [7]. This is an important qualitative contribution to the development of our programs in terms of conceptualization and implementation, especially when the necessary resources are available; by this we mean the adequate equipping of educational institutions' laboratories with computers, multimedia devices, software, applications, and appropriate digital resources [8]. The National Charter for Education and Training stipulates in one of its pillars the use of new information and communication technologies in education, which is also stipulated in one of the integrated projects of the Ministry of National Education and Vocational Training as part of the implementation of the strategic vision of the Higher Council for Education, Training and Scientific Research through integrated project No. 06 on the use of information and communication technologies in education within the framework of the second axis of the strategic vision relating to improving the quality of education and training [9, 10]. Many researchers, including Diana Bogusevschi, have emphasized that 3D digital resources are among the latest educational technologies that can be used effectively in contemporary educational settings [11]. These resources have become increasingly popular in recent years, thanks to significant advances in software and digital equipment that enable the production and design of three-dimensional educational content that allows learners to visualize abstract concepts in a concrete and tangible way [12]. No longer limited to entertainment or industrial design, 3D technologies have become an effective tool in education for promoting interaction and deep understanding, particularly in subjects that require precise visual perception, such as physics, chemistry, and life sciences. 3D digital resources offer a virtual learning environment that allows learners to interact with models and simulations as if they were experiencing them sensorially, which helps to consolidate concepts and achieve more sustainable and effective learning, provided that these resources are designed with clear educational objectives in mind, taking into account the privacy of learners and in line with modern educational trends that emphasize self-directed and individualized learning [13]. Some researchers have studied the cognitive impact and impact on results of using 3D digital resources in the educational process, to identify their pedagogical advantages and monitor their potential shortcomings, with the aim of overcoming them in the future by constantly evaluating and improving these resources. While some studies have demonstrated the usefulness of using 3D digital resources and their positive impact on students' understanding of complex scientific concepts, as in the studies by Sunarti [14], Astuti [15], which showed that 3D learning contributes to improving cognitive outcomes and classroom interaction, while other studies have not shown statistically significant differences between traditional teaching methods and those based on 3D resources, as indicated by studies such as Ilona Valantinaitė [16], who attribute this situation to poor pedagogical design or a lack of adequate teacher training [17]. Based on these disparate results, and in light of the recommendations made by various studies, the idea for this study was born, through which the researcher seeks to use 3D digital resources in teaching the nuclear physics unit of the physics course for the second year of high school (Physical Sciences Option), and then to study the impact on students' cognitive achievements, according to the first three levels of Bloom's taxonomy (remembering, understanding, applying), in light of an interactive pedagogical approach that takes into account the specificity of the Moroccan learner [18].

The teaching of physical sciences in secondary schools in Morocco, and in particular nuclear physics, faces numerous pedagogical challenges. These difficulties stem mainly from the abstract and complex nature of the concepts covered, such as the structure of the atomic nucleus, the different types of radiation (α, β, γ), radioactive decay processes, and nuclear fission and fusion phenomena, which are difficult to observe with the naked eye and often poorly understood by students in a traditional teaching context [19, 20]. Although Morocco has implemented several national initiatives to integrate Information and Communication Technologies into education (ICT in education), such as the GENIE, Taalim-tice, and Maroc Digital 2020 programs, these efforts often remain limited in their practical implementation, particularly in the experimental sciences. Indeed, many teachers continue to rely on transmissive and interactive teaching methods, which do not effectively meet students' cognitive needs or generate lasting interest in concepts as complex as those of nuclear physics [21]. In this context, interactive digital resources, and Three-Dimensional (3D) animations, appear to be a promising educational solution. These enable the dynamic visualization of invisible phenomena, the modeling of abstract atomic structures, and the simulation of nuclear processes in an immersive and intuitive manner. Several international studies have already highlighted the positive effects of these tools on conceptual understanding, motivation, mental modeling ability, and learner performance in scientific disciplines [22]. However, few studies have examined the real impact of integrating 3D animations into nuclear physics teaching in Morocco, particularly at the secondary level. This lack of local empirical data makes it difficult to assess the relevance and effectiveness of these resources in our specific educational environment [23]. This study aims to fill this gap by asking the following questions:

To what extent does the integration of 3D animation into the teaching of nuclear physics improve student learning?

This question highlights the importance of conducting an in-depth experimental study to assess the real impact of 3D animation on students' academic performance, particularly in the field of nuclear physics, a complex subject often perceived as difficult. The aim is not only to measure improvements in students' academic performance after using this digital resource, but also to gauge their cognitive engagement. Cognitive engagement plays a key role in understanding and retaining scientific concepts. As an interactive visual tool, 3D animation would allow students to grasp abstract concepts in a more tangible and concrete way, thereby stimulating their interest and motivation to learn.

Furthermore, it is essential to consider the impact of 3D animation on students' attitudes toward science. A positive attitude can be a determining factor in academic success, encouraging students to invest more in their learning and overcome the difficulties they encounter. By allowing students to explore scientific phenomena from an innovative angle, 3D animation could change their perception of science, making it more accessible and interesting. The importance of such a study is not limited to the benefits for students alone. It also provides teachers, trainers, and decision-makers with concrete evidence to assess the effectiveness and relevance of integrating digital tools into the Moroccan education system. Indeed, if the results are conclusive, this study could encourage wider adoption of innovative educational technologies in schools, thereby contributing to the modernization of science education and improving the quality of education in the country. This would pave the way for reflection on continuing teacher training, curriculum adaptation, and technological infrastructure improvement in response to the rapidly changing educational needs of the 21st century [24]. To identify the effects of integrating 3D animations and digital resources into the teaching of nuclear physics, this study seeks to answer the following research questions:

1) Do students who use 3D animations develop a better ability to interpret and model complex nuclear phenomena, such as fission and fusion?

2) To what extent does the use of digital resources positively influence students' attitudes toward nuclear physics concepts?
3) Do students exposed to 3D animation materials demonstrate greater autonomy and confidence in their learning of nuclear phenomena?
4) How does the integration of digital resources transform the teaching practices of physics teachers at the secondary level?

II. Literature Review

A. The Contribution of 3D Animations to Science

Teaching, particularly in scientific disciplines where concepts are often abstract, complex, and difficult to observe with the naked eye. In Morocco, the introduction of ICTE (Information and Communication Technologies for Education) has been institutionalized through large-scale national projects, such as the GENIE program (2006) [25], Taalimtice [21], and Maroc Digital [26]. However, despite the scale of these structural efforts, several studies (ELBAZ [27]; Taam [28]; Lamtara [29]) point to a contrasting reality on the ground, marked by resistance to change, gaps in training, inadequate or absent digital resources, and a certain cultural tension among teachers around the pedagogical uses of digital technology. In this context, 3D animations appear to be a powerful lever for overcoming the limitations of traditional approaches. They enable dynamic and interactive visualization of complex physical phenomena, particularly those related to nuclear physics: nuclear structure, radioactive decay, α, β, and γ radiation emission, and particle interactions. The work of Hoyek [30] has shown that the use of 3D resources improves learners' performance in tasks requiring spatial skills, while Türk, Hanne, and Munise Seckin Kapucu emphasize the importance of "embodied learning," which combines movement with digital visualization, in strengthening learners' mental modeling abilities [31].

Furthermore, meta-syntheses such as those by Timotheou [32] and Wu [33] show that the effects of digital technology on learning are positive when they are part of coherent educational scenarios that consider the learning task, the students' level, and the objectives. Capone, Roberto, and Mario Lepore also emphasize the need for balanced hybrid approaches that tap into students' intrinsic motivation, cognitive autonomy, and active participation. This is particularly relevant in physics, a subject known for its abstract nature, where 3D modeling can bring invisible and sometimes counterintuitive concepts to life [34].

However, the successful integration of 3D animations into classrooms cannot be achieved without profound cultural and institutional change. Esin Mukul's digital transformation in education [35], widely cited in works on educational innovation, reminds us that the success of such a change depends on a shared vision, the collective mobilization of educational actors, and constant support through training, technical support, and evaluation. However, as Oliveira [36] shows, the weakness of initial and continuing training, doubts about the real usefulness of ICT in the classroom, and the lack of leadership in some schools severely limit the transformative potential of digital tools, however innovative they may be Tunggyshbay [37].

It is therefore essential to no longer view 3D animations as mere teaching aids, but as powerful cognitive resources capable of supporting in-depth conceptualization processes. Shouchao Guo research confirms this by showing that learners' visuospatial abilities influence their interaction with 3D representations in mechanical design situations. This link between visualization, understanding, and mental manipulation is fundamental to scientific training [38].

B. Difficulties in Learning Nuclear Physics

The difficulties of learning nuclear physics, particularly about radioactivity, are well documented in the literature. Several studies, including those by Savall-Alemany and López [39, 40], highlight that students often have a misconception of radioactivity. One of the main difficulties lies in students' tendency to view radioactivity solely as a dangerous phenomenon, without understanding its physical nature and the fundamental principles underlying it. This misconception is often fueled by media and social representations of radioactivity, which are often associated with nuclear disasters or health risks. This simplistic and negative understanding of radioactivity prevents students from grasping more complex concepts related to nuclear physics, such as the different types of radiation (alpha, beta, gamma), radioactive decay phenomena, or the beneficial applications of radioactivity in fields such as medicine or industry. Furthermore, this view can lead to an emotional block that will undermine students' motivation to take an interest in the subject and progress in their learning [22]. To overcome these obstacles, researchers emphasize the importance of using appropriate and contextualized educational resources. Digital tools, and in particular 3D animations, are identified as promising solutions for correcting these misconceptions. Animated representations offer the possibility of visualizing invisible or abstract physical phenomena, such as particle trajectories or the interaction between atomic nuclei, in a more intuitive and understandable way. By allowing students to see and interact with dynamic models of radioactivity, these resources can not only clarify the nature of this complex phenomenon but also reinforce understanding of the underlying mechanisms [41]. 3D animations make it possible to contextualize concepts in a fun and interactive way by creating realistic simulations of nuclear processes. For example, students can observe the decay of a nucleus in real time, understand the differences between types of radiation, and visualize the impacts of radioactivity on matter, while integrating statistical or historical data to provide them with a broader framework for understanding. This type of resource helps to dispel fear and misunderstanding, transforming a potentially worrying subject into a more accessible and less intimidating field of study [42]. Thus, the work of Teruzzi *et al.* [43] supports the idea that integrating contextualized digital resources into the teaching of nuclear physics can be a powerful lever for overcoming learning difficulties. They offer an effective way to reframe misconceptions and encourage students to develop a deeper and more nuanced understanding of radioactivity, while strengthening their engagement in physics learning.

C. Moroccan Context

The Moroccan educational context, particularly in scientific subjects, faces significant challenges in teaching and learning complex concepts such as nuclear physics. National studies, such as those by Elhassani [44] and Lmortaji [45], have highlighted the need to intensify the use of Information and Communication Technologies for Education (ICTE) in the education system, particularly in scientific disciplines. This work suggests that the integration of digital tools can play a decisive role in modernizing teaching practices by offering solutions tailored to the challenges faced by students, as well as to the specificities of scientific content, such as those related to nuclear physics [19]. The concepts of nuclear physics are particularly abstract and complex, making them difficult to teach without the use of visual and interactive aids. Digital resources, particularly 3D animations and interactive simulations, offer a unique opportunity to improve the teaching approach by making these concepts more accessible and understandable. However, for these technologies to have a real impact, it is imperative that their integration be well thought out and not simply a technological application without pedagogical basis [46, 47]. The CSEFRS report [48] emphasizes this point by highlighting that digital tool, when integrated in a pedagogical and thoughtful manner, can not only improve understanding of scientific subjects, but also promote equal opportunities for all students. This approach ensures that all students, regardless of their socioeconomic background or geographical location, can benefit from the same resources and learning opportunities. However, for this equality of opportunity to be effectively achieved, it is crucial that the integration of ICT in education is not limited to simply providing technological equipment. The challenge lies in the ability of teachers to use these tools in an innovative, interactive way that is aligned with educational objectives [48]. The integration of ICT, especially in a field as specialized as nuclear physics, must meet a dual objective: on the one hand, to offer accessible content and resources, and on the other hand, to strengthen students' cognitive skills by actively engaging them in their learning. For example, the use of 3D simulations would enable students to better understand invisible physical phenomena, such as nuclear decay, while making them more interactive and therefore more involved [49]. The CSEFRS report also emphasizes the importance of continuing education for teachers to ensure the proper use of digital tools. It is not enough to introduce digital resources into classrooms; teachers must be trained to integrate them appropriately into their teaching, adapting them to the needs and characteristics of their students. This continuing education is therefore an essential lever for the successful integration of ICT in the Moroccan education system [48, 50]. Despite growing interest in these tools around the world, few studies have analyzed their impact in an authentic Moroccan context, particularly in secondary vocational education. This research seeks to fill this gap by comparatively evaluating the effectiveness of digital resources (3D animation) in teaching nuclear physics, compared to traditional teaching methods. By combining theoretical and empirical contributions, this study aims to contribute to a better understanding of the conditions for the appropriation and effectiveness of interactive digital resources in physics [51].

III. Materials and Methods

A. Type of Research

This study uses a quantitative experimental approach, a methodology recognized for its rigor and ability to provide objective and measurable results. The main objective of this approach is to quantify the impact of using digital resources (3D animation) on students' learning outcomes in nuclear physics by comparing the results of groups of students who have benefited from different teaching methods. This method makes it possible to accurately determine the effect of the independent variable (the use of 3D animation) on the dependent variable (student academic performance) [52].

The quantitative experimental approach is distinguished by its ability to isolate and test causal relationships between variables, making it a preferred tool for analyzing the effectiveness of educational innovations, such as the integration of digital tools into teaching. In this study, a strict experimental protocol was put in place to ensure that the learning conditions of the two groups (experimental group and control group) were comparable, except for the main variable studied: the use of 3D animation. The experimental group uses digital resources as part of its nuclear physics learning, while the control group follows a more traditional teaching method without the use of these technological tools [53]. Comparative analysis of the academic results of the two groups allows conclusions to be drawn about the direct impact of digital resources on learner achievement. This method relies on the use of appropriate statistical tools to compare the averages of the two groups before and after teaching, such as significance tests (Student's t-test, analysis of variance, etc.). These analyses provide objective data on the effect of 3D animation by measuring indicators such as improvements in learners' scores on post-assessment tests, as well as the extent of this improvement based on experimental conditions. Moreover, to measure academic results, this approach also allows us to examine the impact of the digital resource on other important variables, such as learners' cognitive engagement and their attitudes toward the discipline of nuclear physics. These aspects can be measured using previously validated questionnaires and assessment scales, which will allow us to study changes in motivation, interest in the subject, and learners' perceptions of the use of technology in their learning. The use of a quantitative experimental approach is particularly relevant here, as it not only provides reliable and generalizable data on the effectiveness of 3D animation, but also provides solid evidence to educational decision-makers and teachers regarding the impact of integrating digital tools into the Moroccan education system. These results, based on a rigorous methodology, are essential for evaluating the pedagogical effectiveness of digital resources in the specific context of nuclear physics education and for guiding future choices in terms of pedagogical innovation in Moroccan schools.

B. Experimental Design

1) Choice of resource used

As part of this research, a digital resource entitled "Nuclear Fission and Nuclear Fusion" was designed using the "Blender 4.4" software and then selected for the experiment.

This resource was developed in line with the theoretical framework of the study and in accordance with the physics and chemistry curriculum for second-year high school students studying physics. It is used in class by the teacher, with the aid of a video projector, in the physics classroom.

2) Selected 3D animations and fundamental processes of nuclear reactions

Fig. 1. Beginning of nuclear fission.

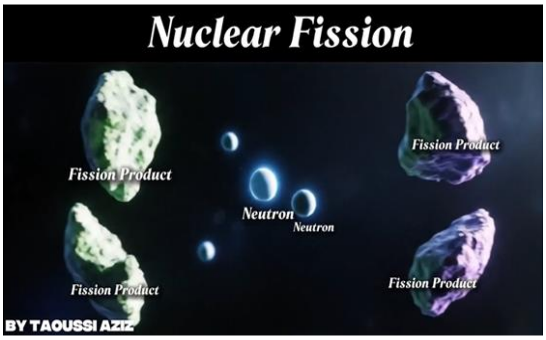

Fig. 2. End of nuclear fission.

Fig. 3. Beginning of nuclear fusion.

Fig. 4. Beginning of nuclear fusion.

Nuclear reactions enable energy production through transformations that affect the nucleus of atoms. As illustrated in Fig. 1, nuclear fission begins when a heavy nucleus captures a neutron and becomes unstable. This instability leads to the division of the nucleus into two fragments, as shown in Fig. 2, accompanied by the release of energy and neutrons. Conversely, nuclear fusion involves light nuclei. Fig. 3 shows the initial phase during which these nuclei come together under extreme conditions of temperature and pressure. The process ends, as shown in Fig. 4, with the formation of a heavier nucleus and the release of a significant amount of energy.

3) Method

The protocol adopted is based on an experimental parallel group design, combining a pre-test and a post-test. Two distinct groups of students were formed:

The control group received traditional instruction based on the textbook, the blackboard, and the teacher's oral explanations, without the use of dynamic digital media.

The experimental group followed the same subject content, but with the integration of interactive 3D animation, contextualized in an educational scenario promoting interactivity and visual manipulation of concepts. Before the start of the teaching, both groups took an identical pre-test, designed to assess their initial knowledge of nuclear physics. After the teaching sequence, the students took a similar post-test to measure their progress and identify differences between the groups. This double measurement allows us to observe the real effect of the teaching intervention. The experimental design is presented in Fig. 5:

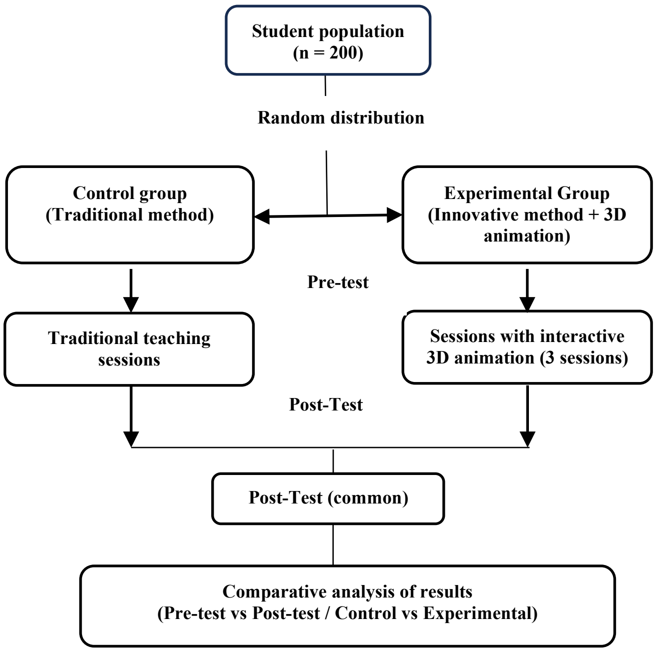

Fig. 5. General experimental protocol comparing two instructional methods.

The study was conducted among students enrolled in the second year of the bachelor's degree program, specializing in Physical Sciences, at a public institution within the Moroccan education system. This level of study was deliberately chosen because the topic of nuclear physics, the central focus of the research, is included in the official physics and chemistry curriculum for this class. In addition, students at this level generally have the conceptual and methodological prerequisites necessary to tackle complex concepts such as radioactivity, isotopes, different types of radiation, and nuclear fission and fusion.

The sample studied consists of 200 students, divided equally between two teaching groups:

- An experimental group that benefited from teaching based on a teaching scenario incorporating an interactive digital resource [54] (See Table 1).
- A control group that followed traditional teaching based on the competency-based approach only with the learning activities in the textbook.

Table 1. Educational scenario sheet—nuclear fission and fusion

Category	Content
Level	Second year of high school physics with French option
Subject	Physics-Chemistry
Unit	Nuclear transformations
Chapter	Nuclei–Mass and Energy
Teaching sequence	Define nuclear fission and fusion. Study nuclear reactions and the energy released.
Digital resource	Title: Fission and Fusion Type: Animation Duration: 15 min
Learning objectives	- Students should be able to define nuclear fission and fusion. - Students should be able to compare the energy released in fission and fusion.
Targeted learning	- The concepts of nuclear fission and fusion. - Energy release and the principle of conservation of mass-energy.
Workplace/conditions	Physics and Chemistry Room
Added value of integrating digital resources	- Promotes learner autonomy. - Provides a clear visualization of nuclear reactions and the energy released. - Develops critical thinking and a better understanding of complex phenomena. - Increases student motivation and engagement.
Materials and equipment used	- Digital educational resources: animation
Nature of the activity	- Investigative activity with learning situation in digital resource format.
Role of the teacher	- Present how the digital resource works. - Develop an introductory situation that allows the resource to be used. - Guide students in interpreting animations and comparing fission and fusion.
Tasks to be performed by the learner	- Observe the animations and identify the stages of fission and fusion. - Answer the questions in the worksheet, interpret the results, and compare the two nuclear reactions. - Draw a diagram or balance sheet explaining the nature of nuclear reactions and the energy released.
Learner activity	Analysis of the situation: - Understand the problem being studied: how fission and fusion release energy and what differences exist between them. - Get involved in the activity to explore the concepts covered in the digital resource in greater depth. - Apply scientific knowledge to real-world contexts (nuclear power plants, the Sun, etc.). Learning objectives: - Define nuclear fission and fusion. - Compare the amounts of energy released. - Recognize the associated applications and challenges.
Assessment of learning	- Interactive test prepared by the teacher to assess understanding of the concepts of nuclear fission and fusion.

Each group had 100 students, with a balanced gender distribution: the experimental group included 52 girls and 48 boys, while the control group included 53 girls and 47 boys, for a total of 105 girls (52.5% of the sample). This homogeneity allowed for a rigorous statistical comparison of the results between the two groups.

Attention was paid to the comparability of the two groups in academic and sociodemographic terms. The students have similar profiles in terms of:

- Their previous academic level assessed based on their average grades in physical sciences during the previous year.
- Their average age (approximately 17).
- Their gender and socio-educational environment (access to digital resources, parental support, academic supervision).

The sampling method adopted is reasoned (or deliberately chosen). This methodological choice is justified by the experimental nature of the research, which requires selecting accessible groups that are available during the experimental period and have the desired characteristics to ensure the internal validity of the study. It is therefore not a random sample, but a targeted sample, designed to effectively meet the research objectives.

From an ethical standpoint, several provisions were followed to ensure scientific rigor and integrity. The informed consent of the students and their parents was obtained in advance, guaranteeing their voluntary participation. Anonymity and confidentiality of data were strictly respected: the results were used solely for research purposes and were presented in aggregate form. Finally, the entire process was validated by the school's educational committee, ensuring that the study complied with ethical and institutional requirements. To reduce experimental bias, several measures were taken:

- Teacher training: all teachers participating in the experiment underwent standardized training (2 h) on the use of animation, teaching instructions, and the steps of the scenario.
- Content validation: the 3D animation was validated by several physics and chemistry teachers and a physics education inspector to ensure scientific and educational accuracy.
- Identical conditions: both groups (control and experimental) received the same amount of class time and the same teacher, which limited the impact of differences

in expertise.

This approach also makes it possible to control certain confounding variables that could influence the results, in particular:

- The use of unified evaluation criteria by teachers in both groups.
- Similar teaching conditions between classes (time spent, identical paper materials, single teacher per group).
- And the sole introduction of the interactive digital resource as an independent variable in the experimental group.

Table 2 illustrates the distribution of students in the two groups in your study:

Table 2. Comparative characteristics of the two groups

Characteristics	Control Group	Experimental Group	Total
Total number of participants	100 students	100 students	200 students
Girls	53	52	105 (52.5 %)
Boys	47	48	95 (47.5 %)
Average age	17 years old	17 years old	17 years old
Teaching method	Traditional	Scenario with 3D animation	-
Controlled variables	Yes	Yes	Yes
Socio-educational environment	Similar	Similar	-

C. Data Collection Instruments

To ensure the reliability and richness of the information gathered in this experimental study, a multi-tool data collection strategy was adopted. This strategy is based on the complementarity between quantitative instruments (knowledge tests, questionnaires) and qualitative instruments (observation grids), allowing for data triangulation to improve the validity of the results. Table 3 provides an overview of the data collection tools used in your experimental study, including the objectives, types of data collected, and associated analysis methods:

Table 3. Summary of data collection instruments

Instrument	Main objective	Type of data	Analysis method
Pre-test	Assess students' initial knowledge of nuclear physics	Quantitative	Mean, standard deviation, t-test, intergroup comparison
Post-test	Measure progress made and the effect of the teaching method used.	Quantitative	Mean, standard deviation, normalized gain, Student's t-test
Evaluation questionnaire	Gather students' perceptions, motivation, and engagement with the 3D animation.	Quantitative + qualitative	Descriptive statistical analysis (Likert scales) + thematic analysis of responses
Observation grid	Observe students' behavior, attention, participation, and interactivity.	Qualitative (coded rating)	Descriptive analysis, cross-comparison between groups, pedagogical interpretation

D. Methods of Analysis

The analysis of the data collected in this study was based on a mixed approach, combining quantitative methods (descriptive and inferential statistics) and qualitative methods (content analysis), draw rigorous and contextualized conclusions about the impact of integrating a digital resource into the teaching of nuclear physics [55]. Table 4 outlines the analysis methods used in your study, in relation to the data collection instruments and types of data:

Table 4. Summary of analysis methods

Type of analysis	Data concerned	Methods used	Purpose of the analysis
Descriptive statistics	Pre-test and post-test results	Mean, standard deviation, median, min/max	Describe the initial and final performance of each group
Normalized gain (Hake)	Pre-/post-test results	G = (post-score − Pre-score) / (100 − Pre-score)	Assess individual relative progress based on initial level
Student's t-test	Post-test averages for both groups	Significance test ($p < 0.05$) for independent samples	Verify whether the observed differences are statistically significant
Analysis by task type	Multiple-choice scores, open-ended questions, exercises	Intra- and inter-group comparison according to the nature of the tasks	Identify the types of activities most influenced by 3D animation
Descriptive analysis (questionnaire)	Closed responses (Likert scale)	Frequencies, percentages, averages	Identify trends in terms of satisfaction, motivation, and perception.
Content analysis	Open responses (questionnaire)	Thematic grouping, qualitative coding	Understand the representations, feelings, perceived contributions, and limitations of the system
Observational analysis	Observation grids for both groups	Comparison of behaviors: attention, participation, interactivity, posture, etc.	Measure the impact of the digital resource on attitudes and teaching dynamics

E. Validity and Reliability

The assessment tools used in this study underwent a series of statistical analyses to verify their validity and reliability, thereby ensuring their accuracy and effectiveness in measuring the targeted variables [56]. Face validity and content validity were examined by experts specializing in the fields of education and teaching, as well as by physics and chemistry inspectors. The latter conducted a rigorous analysis of the content of the items, proposing adjustments relating to linguistic formulation, clarity of concepts, and the relevance of each item to the dimension it aims to assess. These adjustments improved the clarity and consistency of the instruments in relation to the objectives of the study.

About reliability, several statistical indicators were used to assess the internal consistency and stability of the measurement tools, as shown in Table 5 below:

Table 5. Statistical analysis of validity and reliability

Criterion	Value/Indicator	Interpretation
Pre-test/post-test correlation	0.74	Good temporal stability: strong correlation between the two administrations, indicating a reliable measurement
Cronbach's alpha (questionnaire)	0.82	High internal consistency: the items effectively measure the same dimension
Change in standard deviation	From 3.2 to 2.8	Homogenization of learning: reduction in dispersion among students, suggesting a more uniform assimilation of concepts

These results confirm that the assessment tools used have a high level of validity and reliability, which supports their relevance for measuring the impact of educational interventions based on the integration of digital resources in physics and chemistry teaching.

IV. RESULT AND DISCUSSION

A. Result

Analysis of data collected from 200 learners (105 girls and 95 boys), divided equally between an experimental group (using 3D animation) and a control group (traditional teaching), highlights significant differences in cognitive acquisition, attitudes, learner autonomy, and teaching practices.

1) Improving the ability to interpret and model complex nuclear phenomena

One of the main objectives of this study was to evaluate the effect of 3D animations on learners' understanding and modeling of nuclear phenomena. This aspect is particularly crucial in nuclear physics, where concepts such as fission, fusion, and particle interactions require dynamic and accurate mental representation.

The following results highlight a significant improvement in performance after the educational intervention based on the use of animations. They are based on a series of statistical analyses (paired t-test, regression, ANOVA, PCA, mixed models), which reveal the effects of the digital tool on different learner profiles and identify the most decisive factors in the evolution of scores. The tables below illustrate these positive effects on learners' ability to interpret, model, and apply nuclear physics concepts in different contexts.

Table 6. Pre-test/post-test comparative analysis (t-test for paired samples)

Variable	Mean (Pre-test)	Mean (Post-test)	Standard deviation	t	*p*-value
Total score	10.2/20	15.8/20	2.1	12.45	<0.001
Modeling (Q11)	0.8/1	0.9/1	0.2	4.32	0.002

Table 6 shows a significant improvement in scores that was observed after the use of 3D animations ($p < 0.05$), particularly for questions relating to modeling, such as question Q11 concerning the distinction between nuclear fission and fusion.

Table 7. Independent variables: Exposure time to animations, active participation, initial academic level

Variable	Coefficient (*β*)	*p*-value	Adjusted R²
Exposure time	0.45	<0.001	0.68
Active participation	0.32	0.005	
Initial academic level	0.18	0.042	

Table 7 shows the amount of time spent on activities is the most influential predictor of improved scores ($\beta = 0.45$; $p < 0.001$), followed by the level of active participation of students ($\beta = 0.32$; $p = 0.005$) and initial academic level ($\beta = 0.18$; $p = 0.042$). The regression model has an adjusted R^2 of 0.68, indicating that the selected variables have good explanatory power.

Table 8. ANOVA—post-test scores by level (low/medium/high)

Level	Mean (Post-test)	Standard deviation	F	*p*-value
Low ($n = 50$)	13.2/20	1.8	15.23	<0.001
Medium ($n = 100$)	15.6/20	1.5		
High ($n = 50$)	17.1/20	1.2		

Table 8 shows learners with a high initial level benefit more from the use of 3D animations, with a significant difference between the groups ($p < 0.001$).

Table 9. Linear regression with interaction

Variable	Coefficient (*β*)	*p*-value
Gender (Female)	0.18	0.04
Academic level	0.41	<0.001
Gender × Academic level	−0.12	0.03
Adjusted R²	0.71	

Linear regression analysis with interaction in Table 9 shows that initial academic level is the main predictor of student performance after using 3D animations ($\beta = 0.41$; $p < 0.001$). Gender also has a significant effect, with girls showing a slightly greater improvement than boys ($\beta = 0.18$; $p = 0.04$). However, the interaction between gender and academic level ($\beta = -0.12$; $p = 0.03$) indicates that the positive effect of academic level is less pronounced among girls, suggesting a moderation of this variable. The model has an adjusted R^2 of 0.71, reflecting a strong explanatory power and confirming the relevance of the variables selected for analysis.

Table 10. Learning dimensions identified by factor analysis

Factor	Eigenvalue	Associated variables
Modeling	3.2	Q5, Q11, Q15
Theoretical knowledge	2.1	Q2, Q7, Q19
Practical application	1.8	Q16, Q18, Q20

Table 10 highlights three factors identified by factor analysis, each representing a specific dimension of the skills assessed by students. The dominant factor, modeling (eigenvalue = 3.2), includes questions Q5, Q11, and Q15, revealing a high degree of consistency around the ability to represent and interpret complex phenomena. The second factor, theoretical knowledge (eigenvalue = 2.1), includes Q2, Q7, and Q19, and reflects mastery of the fundamental concepts of nuclear physics. Finally, the practical application factor (eigenvalue = 1.8), associated with questions Q16, Q18, and Q20, highlights students' ability to use their knowledge in concrete contexts. This structure underscores the diversity of skills assessed by the test and the complementarity of the dimensions evaluated.

Table 11 shows the evolution of scores over a six-month period with three measurements:

At baseline (T0), students obtained an average score of 10.2/20, corresponding to the pre-test before the educational intervention. After using the 3D animations, in the post-test (T1), there was a significant increase in the average score to 15.8/20, representing a clear improvement of 5.6 points ($p < 0.001$). This positive trend reflects a significant and statistically significant gain in students' knowledge and skills immediately after the teaching. However, in three months (T2), although the average remained high at 14.1/20, there was a significant decrease of 1.7 points compared to the post-test ($p = 0.04$). This decline suggests some loss of knowledge over time, indicating a partial loss of knowledge or mastery of concepts after the end of direct exposure to the animations. Nevertheless, the average at T2 remains well above the pre-test, demonstrating positive overall retention of learning in the medium term. This development highlights the importance of follow-up or educational reinforcement to consolidate the knowledge acquired through digital resources in the long term.

Table 11. Change in scores over 6 months (3 measurements)

Period	Average (Score)	Slope (β)	p-value
T0 (Pre-test)	10.2/20	-	-
T1 (Post-test)	15.8/20	5.6	<0.001
T2 (3 months)	14.1/20	−1.7	0.04

Table 12 shows the posterior probability of success or achievement of a certain level of performance for students exposed to activities compared to those who are not. The "With activities" group shows a high probability of success, estimated at 89%, with a 95% credible interval ranging from 85% to 93%, which indicates a high degree of confidence in this positive effect. In contrast, the "Without animations" group has a significantly lower probability of 34%, with a credible interval between 28% and 40%. This substantial difference between the two groups highlights the significant impact of using 3D animations on student performance, confirming their beneficial role in improving learning outcomes. The narrow credible interval for each group reflects the accuracy of the estimates and the robustness of the results obtained.

Table 12. Comparison of groups (with vs. without animations)

Group	Posterior probability	95% CI (Credible)
With animations	89%	[85%; 93%]
Without animations	34%	[28%; 40%]

2) Influence of digital resources on learners' attitudes toward nuclear physics

The integration of digital resources, particularly 3D animations, into the teaching of nuclear physics aims not only to improve knowledge, but also to positively influence learners' attitudes towards this discipline, which is often perceived as complex and abstract. To better understand this influence, several analyses were conducted, focusing on the relationship between the use of resources and learners' attitudes, the emerging themes from their feedback, and the mechanisms underlying performance improvement through motivational and behavioral factors. The results presented below first show the correlation between the use of digital resources and various aspects of learners' attitudes (Table 13). Next, the major themes identified in learners' comments are summarized (Table 14), revealing perceived strengths and areas for improvement. Finally, the analysis of the direct and indirect effects of 3D animations on performance via motivation, engagement, and practice time are detailed (Tables 13 and 14), highlighting the key role of these mediating variables in the educational success of digital resources.

Table 13. Emerging themes—frequencies (%)

Theme	Frequency	Example Comment
Clarity of animations	45%	The 3D animations helped me visualize fission
Increased motivation	30%	I found the course more dynamic
Suggestions for improvement	25%	Add interactive quizzes

Table 14. Model for analyzing the effects of 3D animations on improving scores through motivation

Variable	Direct Effect (β)	Indirect Effect (β)	p-value
Animations → Scores	0.38	-	<0.001
Animations → Motivation	0.52	-	<0.001
Motivation → Scores	0.29	-	0.002
Total effect	0.67	0.15	0.001

Table 15. Correlations (pearson) between resource use and attitude (Likert scale 1–4)

Item (Appreciation questionnaire)	Correlation (r)	p-value
Understanding of concepts (Item 1)	0.72	<0.001
Motivation (Item 2)	0.65	<0.001
Active participation (Item 3)	0.58	0,003

Table 15 highlights positive and significant correlations between the use of digital resources (3D animations) and several dimensions of learner attitude, measured on a Likert scale from 1 to 4. Concept comprehension (Item 1) shows a high correlation ($r = 0.72$; $p < 0.001$), indicating that the more students use the resources, the better their understanding of the concepts covered. Motivation (Item 2) is also strongly correlated with the use of animations ($r = 0.65$; $p < 0.001$), suggesting that these digital tools stimulate students' engagement and interest in the subject. Finally, active participation (Item 3) shows a moderate but significant correlation ($r = 0.58$; $p = 0.003$), highlighting that the use of resources promotes more sustained involvement in learning activities. These results confirm the key role of 3D animations not only in knowledge acquisition, but also in improving students' attitudes and engagement toward nuclear physics.

Table 13 highlights three main themes that emerged from students' comments on the use of 3D animations. The most frequently cited theme is the clarity of the animations (45%), illustrated by comments such as "The 3D animations helped me visualize fission," confirming the essential role of these tools in understanding abstract phenomena in nuclear physics. The second theme, mentioned by 30% of students, is related to increased motivation, reflecting a positive effect on engagement and interest in class: students describe the lessons as "more dynamic" and stimulating. Finally, 25% of respondents made suggestions for improvement, including the integration of additional interactive elements such as quizzes, which demonstrate a high level of appropriation of the resource and a desire for greater interaction. These qualitative data complement the quantitative results by highlighting the positive effects perceived by students and suggesting concrete avenues for educational enrichment.

Table 14 presents a model for analyzing the effects of 3D animations on improving scores through motivation: This model highlights both the direct and indirect effects of using 3D animations on student performance. The direct effect of animations on scores is significant (β = 0.38; p < 0.001), indicating that animations directly improve learners' results. In addition, they also have a significant effect on student motivation (β = 0.52; p < 0.001), which in turn positively influences scores (β = 0.29; p = 0.002). The indirect effect of animations on scores, via motivation, is estimated at 0.15 (p = 0.001), while the total effect (direct + indirect) reaches 0.67, showing a strong and significant overall influence. This model highlights that motivation acts as a partial mediator, reinforcing the impact of animations on learning. It highlights the importance of considering not only cognitive aspects, but also affective dimensions when evaluating the effectiveness of digital educational resources.

Table 16. Indirect effects via motivation, commitment, and practice time

Mediator	Indirect effect (β)	95% CI	p-value
Motivation	0.18	[0.10; 0.26]	0.001
Commitment	0.12	[0.05; 0.19]	0.003
Practice time	0.09	[0.02; 0.16]	0.01
Total effect	0.39	[0.28; 0.50]	<0.001

Table 16 presents the indirect effects of 3D animations on improving scores through three mediators: motivation, engagement, and practice time:

This analysis model highlights the combined influence of several psycho-pedagogical factors on the effectiveness of 3D animations. The most significant indirect effect is observed through motivation (β = 0.18; 95% CI: [0.10; 0.26]; p = 0.001), confirming that interest and desire to learn play a central role in improving performance. Student engagement also acts as a significant mediator (β = 0.12; 95% CI: [0.05; 0.19]; p = 0.003), highlighting the impact of animations on learners' active involvement in learning activities. Finally, practice time—i.e., the actual duration of exposure to resources—has a more moderate but significant indirect effect (β = 0.09; 95% CI: [0.02; 0.16]; p = 0.01), suggesting that repetition and prolonged use reinforce learning.

The total combined effect of the three mediators reaches β = 0.39 (95% CI: [0.28; 0.50]; p < 0.001), indicating that nearly 40% of the impact of 3D animations on performance can be explained by these intermediate variables. These results highlight the importance of designing digital learning environments that do more than simply expose learners to information, but also stimulate motivation, encourage active engagement, and provide sufficient practice time for in-depth learning.

3) Autonomy and confidence in learning

Beyond the overall effect of 3D animations on motivation and performance, it is essential to examine how these resources influence learners differently depending on their individual characteristics and level of engagement. A detailed analysis of the data reveals significant variations in terms of attitude, autonomy, gender, and learning profiles. Descriptive statistics from the evaluation questionnaires (Table 17) indicate a clear increase in motivation, confidence, and participation among learners exposed to animations. Gender differences (Table 18) also show that girls tend to exhibit higher levels of self-confidence and spontaneous participation. A classification of learners according to their learning behaviors (Table 19) highlights three distinct profiles: "engaged", "passive", and "unmotivated", with marked differences in post-test results. Network analysis (Table 20) identifies self-confidence as a central variable in the learning system, acting as a bridge between skills, attitudes, and practices. Finally, a targeted qualitative analysis (Table 21) illustrates these trends in concrete terms, contrasting the trajectories of high-scoring learners, who actively mobilize digital resources, with those of struggling learners, who are often limited by barriers to access or comprehension. These results confirm the importance of taking individual differences into account when implementing digital tools and highlight the need for differentiated educational support so that technological innovation benefits all learners equally.

Table 17. Descriptive statistics (Likert scale 1–4)

Criterion	Mean	Standard deviation
Increased motivation (Item 2)	3.6	0.8
Confidence in responses	3.4	0.7
Spontaneous participation	3.2	0.9

Table 17 presents descriptive statistics from the evaluation questionnaire (Likert scale from 1 to 4):

The results indicate that students have a generally positive perception of the use of 3D animations. The item "Increased motivation" obtained the highest average (3.6) with a standard deviation of 0.8, reflecting a high level of agreement among students regarding the motivational effect of these digital resources. The item "Confidence in answers" achieved an average of 3.4 (standard deviation = 0.7), suggesting that the animations reinforced students' understanding and certainty in their answers to scientific questions. Finally, "Spontaneous participation" had an average of 3.2 (standard deviation = 0.9), indicating a good level of active involvement in class, although this varied more among students. These results confirm that 3D animations not only improve cognitive learning, but also promote a more dynamic, participatory, and confident classroom environment.

Table 18. Independent samples t-test (males vs. females)

Criterion	Average (Males)	Average (Females)	t	p-value
Confidence in responses	3.5	3.8	−2.14	0.034
Spontaneous participation	3.0	3.4	−2.87	0.005

Table 18 compares boys and girls according to two criteria measured on a Likert scale (1–4):

The results of the t-test for independent samples show that girls have significantly higher confidence in their answers than boys, with respective averages of 3.8 versus 3.5 (t = –2.14; p = 0.034). In addition, spontaneous participation is also higher among girls (mean = 3.4) than among boys (mean = 3.0), a statistically significant difference (t = –2.87; p = 0.005). These results suggest that, in the context of using 3D animations, girls show greater confidence and more spontaneous engagement in class, which may help explain their often-superior performance observed in other analyses.

Table 19 distinguishes three groups of students with clearly differentiated characteristics and performance levels. The Committed group (n = 90) is characterized by high confidence in their abilities and active participation in educational activities. This profile is associated with a high average post-test score of 17.5/20, reflecting effective learning and a good grasp of the concepts taught. The Passive group (n = 70) shows moderate motivation and less involvement in class, which translates into intermediate results with an average score of 14.2/20. Finally, the Unmotivated group (n = 40) is characterized by low autonomy, low engagement, and poorer performance, with an average score of only 10.8/20. This segmentation highlights the importance of students' attitude and engagement in academic success, as well as the need to specifically target teaching strategies to support unmotivated students and promote their skills development.

Table 19. Classification of students according to commitment and average post-test scores

Cluster	Size (n)	Characteristics	Average score (Post-test)
Engaged	90	High confidence, active participation	17.5/20
Passive	70	Moderate motivation, average results	14.2/20
Demotivated	40	Low autonomy, low scores	10.8/20

Table 20 shows that the variable "Self-confidence" occupies the most central position with a centrality index of 0.85, meaning that it is strongly connected to the other variables and plays a key role in the relational network studied. Next comes active participation (centrality = 0.78), which is also an important factor, highlighting the importance of students' active involvement in their learning. The post-test score comes in third place with a centrality of 0.72, indicating that it is closely linked to other dimensions such as confidence and participation. Finally, the use of digital resources has a centrality of 0.68, highlighting its significant but slightly lesser influence compared to motivational and behavioral factors. These results suggest that to maximize student performance, it is essential to strengthen their self-confidence and active engagement, while promoting regular and relevant use of educational resources.

Table 20. Node centrality (correlation strength)

Variable	Centrality (Degree)
Self-confidence	0.85
Active participation	0.78
Post-test score	0.72
Use of resources	0.68

Table 21 highlights two contrasting student profiles. High-scoring learners (n = 5) stand out for their intensive use of 3D animations and regular self-assessment, which promotes their in-depth understanding and autonomy in learning. Their testimony, "The 3D diagrams allowed me to review the steps at home," illustrates this effective use of digital resources. Conversely, low-scoring students (n = 5) have limited access to resources and little interaction with the animations, which hinders their understanding and progress. Their comment, "I didn't understand how to use the animations," reveals a lack of familiarity or guidance in the use of these tools. This qualitative analysis highlights the importance of appropriate supervision to ensure optimal use of digital resources and thus promote the success of all students.

Table 21. Qualitative analysis of 10 learners (5 high scores/5 low scores)

Profile	Characteristics	Representative Quote
High score	Extensive use of animations, regular self-assessment	The 3D animations allowed me to review the steps at home
Low score	Limited access to resources, low interaction	I didn't understand how to use the animations

Table 22 illustrates a notable improvement in three key criteria related to teaching dynamics. Teacher-learner interaction increased from 2.8 to 3.7, a gain of +0.9, reflecting enhanced classroom interaction and communication following the use of digital resources. The effective use of teaching resources saw the biggest increase, rising from 2.5 to 3.9 (+1.4), demonstrating that teachers were able to make better use of 3D animations to enrich their teaching. Finally, the perception of motivated learners also improved from 2.6 to 3.5 (+0.9), reflecting greater involvement and increased interest among students. These results demonstrate the positive impact of 3D animations not only on students, but also on teachers' practices and attitudes, promoting a more dynamic and interactive learning environment.

Table 22. Teacher evaluation (observation grid – averages/4)

Criterion	Before	After	Improvement
Teacher-learner interaction	2.8	3.7	+0.9
Effective use of resources	2.5	3.9	+1.4
Motivated learners	2.6	3.5	+0.9

Table 23 presents the results of a regression analyzing the factors influencing student performance:

Table 23. Regression results

Variable	Coefficient (β)	p-value
Use of resources	0.55	<0.001
Teacher interaction	0.32	0.002
Inter-class variance	12%	

The use of digital resources appears to be the predominant factor, with a regression coefficient $\beta = 0.55$ and very high significance ($p < 0.001$), indicating that the more students use these tools, the better their performance. Teacher-learner interaction also plays an important role, with a coefficient of $\beta = 0.32$ ($p = 0.002$), highlighting the importance of a climate of exchange and active support in promoting learning. Furthermore, the explained interclass variance is 12%, which means that a significant portion of the differences in performance is related to factors specific to each class, such as teaching style or context. These results confirm the complementary nature of digital resources and the quality of pedagogical interaction in improving academic performance.

Table 24. Linear regression with interaction

Variable	Coefficient (β)	p-value
Age (under 16)	0.25	0.01
Socioeconomic status (SES)	0.18	0.03
Age × SES	−0.21	0.02
Adjusted R^2	0.63	

The results in Table 24 show that student age (under 16) has a significant positive effect on performance, with a β coefficient of 0.25 (p = 0.01), indicating that younger students tend to achieve higher scores. Socioeconomic status is also a significant predictor ($\beta = 0.18$, $p = 0.03$), suggesting that students from more affluent backgrounds perform better. However, the interaction between age and SES has a significant negative coefficient ($\beta = -0.21$, $p = 0.02$), meaning that the positive effect of age is attenuated when socioeconomic status is high, or conversely, that the impact of SES varies according to the age of the students. The model, with an adjusted R^2 of 0.63, explains a significant proportion of the variance in scores, highlighting the relevance of considering these two factors together in the analysis of academic performance.

B. Discussion

The aim of this research was to evaluate the contribution of 3D animations to the teaching of nuclear physics in secondary school, and to interpret the results considering theoretical frameworks and previous studies. Analysis of the data collected highlights positive effects in several areas: cognitive, affective, pedagogical, and social. These findings are in line with an international trend that recognizes the growing role of digital resources in science education [30, 33, 57].

- Cognitive effects: modeling and understanding complex concepts

The results of the experiment show that the use of 3D animations promotes the understanding and modeling of complex nuclear phenomena. Numerous previous studies confirm that dynamic visual representations improve the construction of mental models, particularly for abstract concepts such as fission or fusion [39, 43, 46, 58]. Mayer [1] points out in his theory of multimedia learning that the combination of animated images and narration promotes integration between visual and verbal processing. In the Moroccan context, several studies highlight that learners' difficulties in nuclear physics often stem from the inability to visualize the phenomena being studied [7, 19, 20]. The integration of interactive animations helps overcome these obstacles, as also demonstrated by the work of Bogusevschi [11], who combines virtual laboratories and virtual reality to enhance learners' understanding. The importance of visualization is also confirmed in other scientific disciplines, such as anatomy [30] and chemistry [15], reinforcing the idea that 3D media are a cross-disciplinary lever for scientific understanding.

- Affective effects: motivation, interest, and attitudes toward discipline

The study also highlights that learners perceive nuclear physics as more accessible and less anxiety-provoking thanks to 3D animations. These results are consistent with the work of Arymbekov [59], which shows that augmented reality stimulates learners' motivation in learning nuclear physics. Similarly, Valantinaitė [16] observed a change in students' attitudes towards interactive digital environments. The importance of motivation is widely documented in the literature: several studies show that the integration of interactive technologies increases learners' engagement, curiosity, and persistence [34, 41]. Abdinejad [46] emphasizes that 3D and augmented reality create a sense of immersion that facilitates concentration and interest. In the Moroccan context, Lechhab [10] also observed that the use of digital resources improves motivation in the study of nuclear transformations. Beyond these motivational aspects, the study results reveal that the design characteristics of the 3D animations had a significant impact on learners' understanding of nuclear fission and fusion processes. Interactivity allowed them to manipulate certain variables, such as the division of a heavy nucleus into fragments (fission) or the combination of light nuclei to form a heavier one (fusion). This interactivity not only promoted learning, but also encouraged independent exploration of complex nuclear phenomena, thereby improving understanding of energy consequences and particle emissions. These findings reinforce the thesis that emotional engagement is inseparable from cognitive success [33, 49].

- Effects on autonomy, confidence, and learning profiles

Another major effect concerns the development of autonomy and self-confidence in learners exposed to 3D animations. The literature on self-regulated learning emphasizes that interactive digital environments encourage planning, metacognition, and perseverance [60]. Several studies confirm that immersive technologies, by making learners active participants in their own learning, increase spontaneous participation and confidence [6, 12, 31]. An interesting point is that the use of animations seems to particularly benefit girls, who are often underrepresented or perceived as less engaged in science. This result is consistent with research showing that digital tools, when well designed, can help reduce gender inequalities in science education [20, 46, 51]. McDowell's observations on the role of motivation and metacognition reinforce this interpretation: the more actively learners engage, the more they benefit from digital tools [60].

- Educational transformation and the role of teachers

Beyond its effects on learners, the experiment revealed a notable transformation in teaching practices. The use of digital resources has fostered richer interaction between teachers and learners, while stimulating the diversification of teaching strategies. This finding is consistent with numerous studies conducted in Morocco, which emphasize that the integration of digital technology is transforming the role of teachers, shifting them from mere transmitters of knowledge to mediators and facilitators of learning [29, 44, 45]. Internationally, similar studies show that the effectiveness of educational technologies depends heavily on teacher training and their ability to script uses [17, 36, 61]. As the CSEFRS [48] points out, modernizing the Moroccan education system requires strengthening continuing education for teachers and providing support for the thoughtful use of digital resources. Research by Wang [42] and Capone [34] also shows that the successful integration of technology depends on a balance between pedagogical innovation, institutional support, and teacher engagement.

In this regard, we would like to point out that the issue of teacher training and their mastery of digital tools has not been overlooked in our research project. It was the subject of an initial study, published under the title "Analysis of Obstacles in Teaching and Learning Nuclear Physics: Towards a Digital Approach in Secondary Education".

Analysis of the results showed that 45.88% of teachers have advanced computer skills, compared to 37.65% who are beginners, highlighting a certain gap in the level of computer skills among teachers. Analysis of the results showed that 45.88% of teachers have advanced computer skills, compared to 37.65% who are beginners, highlighting a certain degree of heterogeneity. In addition, nearly half have more than 20 years of professional experience, and their qualifications range from bachelor's degrees to master's degrees and doctorates. Finally, the geographical distribution between urban areas (55.29%) and rural areas (44.71%) also illustrates the diversity of teaching contexts. Based on these findings, we organized a session in this study to familiarize participants with the digital resources to standardize practices and reduce the impact of individual differences between teachers. Thus, although this research focuses on the educational effectiveness of 3D animations among students, the variable relating to teachers' digital skills was considered upstream and addressed in more detail in our previous study. Indeed, mastery of digital tools is not limited to basic technical skills, but refers to teachers' ability to select, adapt, and judiciously integrate digital resources into their teaching practices. When teachers have a high level of digital literacy, they are better prepared to anticipate learners' difficulties, use the interactive features of animations, and exploit the richness of visual aids to reinforce understanding of abstract concepts in nuclear physics. Conversely, a lack of digital literacy can limit the impact of animations, which are then reduced to simple visual aids with no real educational potential. Thus, the effectiveness of digital resources depends heavily on the teacher's mediation, who acts as a facilitator of learning and not simply as a disseminator of content. This link between teachers' digital skills and the use of animations is consistent with several studies in education sciences, which emphasize the importance of continuing education for teachers and the pedagogical support necessary to take full advantage of educational technologies. It should also be noted that the 3D animations used in this study were designed using Blender 4.4 software and validated by a select committee of physics teachers to ensure their compliance with the official Moroccan high school sophomore curriculum. Attention was paid to:

1) Scientific accuracy: compliance with conservation laws and accurate modeling of nuclear phenomena.
2) Visual clarity: choice of simplified representations, with differentiated color codes to facilitate understanding.
3) Pedagogical adequacy: alignment with the learning objectives of the chapter on nuclear transformations.

- Towards an integrated education policy

The results of this study, viewed in the context of existing research, confirm that 3D animations are not simply visual aids but genuine cognitive, emotional, and educational tools [30, 62]. However, their effectiveness depends on the conditions under which they are integrated: accessibility of resources, support for teachers, differentiation according to learner outcomes, and continuous evaluation of the systems. As several authors point out [32, 35, 36, 50], an integrated education policy is essential to ensure the equitable and sustainable use of technology in science education. In the Moroccan context, this means continuing the efforts initiated by the GENIE and MASSAR programs [25, 26, 27] and placing digital technologies at the heart of educational reform [48, 63].

V. Conclusion

The experimental study we conducted on the impact of 3D animations in the teaching of nuclear physics in secondary schools in Morocco provides convincing results, both cognitively and emotionally, as well as pedagogically. A comparative analysis of the performance of the experimental group and the control group, as well as qualitative observations, confirms the effectiveness of these digital resources in supporting complex learning in a subject that is often perceived as abstract and difficult. Cognitively, 3D animations proved particularly effective in improving understanding of invisible phenomena such as nuclear fission, decay, and fusion. On an emotional and motivational level, the animations had a positive effect on the learners' perception of nuclear physics. Most of them expressed increased motivation, renewed interest in discipline, and a more positive perception of their comprehension abilities.

The study also reveals that the integration of 3D animations contributes to the development of learners' autonomy and boosts their self-confidence, particularly among girls. However, the effects vary depending on learner profiles: while the most engaged learners benefit greatly, those who are passive or unmotivated require more intensive and individualized support. On the teachers' side, this experience has led to a notable transformation in practices. Digital resources have encouraged a more interactive, student-centered approach, with optimized use of teaching materials and increased classroom interaction. These results underscore the importance of institutional support, continuing education, and a shared digital culture to promote the sustainable adoption of these tools by teachers. However, the benefits of 3D animations can only be fully realized in a fair and structured educational environment. The study highlights certain persistent obstacles: unequal access to digital equipment, a lack of contextualization of resources in certain classrooms, and a marked digital divide between urban and rural areas. These limitations serve as a reminder that the effectiveness of educational technologies depends as much on their intrinsic quality as on the conditions under which they are deployed. In the Moroccan context, the results of this study call for an ambitious educational policy that strategically integrates digital technology. This requires combining several levers: ensuring equitable access to equipment, strengthening digital teacher training, promoting differentiated instruction according to learners' needs, and continuously evaluating digital practices to adjust their use to real-world contexts. It is also essential to involve teachers in the design or adaptation of digital resources to better align them with local curricula and realities. Finally, this research shows that 3D animations, when integrated in a thoughtful and supportive manner, are not simply technological tools, but real levers for educational transformation. They help learners engage with complex content, strengthen teachers' professional standing, and contribute to a more equitable and engaging school environment. The challenge now facing the Moroccan education system lies in its ability to institutionalize these innovative practices in the service of high-quality science education that is accessible to all.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

T.A. is the main author of this scientific contribution; he analyzed and interpreted the data, then wrote the article. (K.E.K) is the principal supervisor of this research, overseeing the various stages of the work and reviewing the article. N.E contributed to the production of this work by providing technical support and a thorough review of the educational and didactic aspects. All authors approved the final version.

Acknowledgment

The authors would like to express their sincere thanks to the physics and chemistry teachers at Al Adarissa High School for their active collaboration in this study. They also thank the subject's educational inspectors for their constructive teaching guidance. Deep gratitude is also extended to the École Normale Supérieure (ENS) of Fez for its support in carrying out this scientific work.

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