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Simulation-Based Computer-Assisted Instruction and Quantum Physics Learning Outcomes: Evidence on Achievement and Retention from Colleges of Education in North-Central Nigeria

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ABSTRACT

Quantum physics is foundational to contemporary scientific and technological progress, yet students in Nigerian Colleges of Education consistently exhibit low achievement and rapid knowledge decay in the subject. This quasi-experimental study investigated Simulation-Based Computer-Assisted Instruction (Simulation-CAI) on the achievement and retention of Nigeria Certificate in Education (NCE II) Physics students in quantum physics, situated within North Central Nigeria. Grounded in Mayer's Cognitive Theory of Multimedia Learning and Hattie and Timperley's Feedback and Reinforcement Theory, the study adopted a pretest–posttest–post-posttest control group design. A purposive sample of 236 NCE II students drawn from six Colleges of Education was allocated to either a Simulation-CAI experimental group ($n = 113$) or a Conventional Lecture Method control group ($n = 123$). Two validated, highly reliable instruments—the Quantum Physics Achievement Test (QPAT; KR-21 = 0.88) and the Quantum Physics Retention Test (QPRT; KR-21 = 0.84)—were administered at pretest, posttest, and post-posttest intervals. Data were analysed using descriptive statistics and Analysis of Covariance (ANCOVA) at $\alpha = .05$. Results revealed that Simulation-CAI produced no statistically significant advantage over conventional instruction in immediate achievement ($F = 0.306$, $p = .581$, $\eta^2 = .001$); however, Simulation-CAI yielded significantly superior long-term retention ($F = 8.421$, $p = .004$, $\eta^2 = .035$). These findings indicate that Simulation-CAI is particularly effective in consolidating durable conceptual understanding of abstract quantum phenomena. The study contributes novel evidence on the differential impact of simulation technology on immediate versus delayed learning outcomes in physics teacher education within low-resource, high-stakes educational contexts. Implications for curriculum reform, instructional design, and teacher preparation are discussed.

Keywords: Simulation-based CAI; Quantum Physics; Achievement; Retention; Colleges of Education.

1.1 INTRODUCTION

Physics education occupies a privileged position in the global effort to cultivate scientific literacy, technological innovation, and sustainable national development. Within the discipline of physics, quantum physics represents one of the most intellectually demanding yet strategically consequential domains of knowledge. It constitutes the theoretical scaffold upon which transformative modern technologies—semiconductors, lasers, magnetic resonance imaging, quantum cryptography, and the rapidly evolving field of quantum computing—are constructed (Krijtenburg-Lewerissa et al., 2019; Michael et al., 2020). As such, producing graduates who possess robust, durable conceptual understanding of quantum phenomena is not merely an academic ambition but a national imperative. In Nigeria, Colleges of Education are constitutionally mandated to train the next generation of physics teachers for basic and secondary education. The Nigeria Certificate in Education (NCE) physics curriculum introduces quantum physics in the second year, encompassing wave-particle duality, quantum states and superposition, energy quantisation, Heisenberg's uncertainty principle, and quantum tunnelling. Despite its centrality, research consistently documents that students in Nigerian Colleges of Education—particularly within the North Central Zone—perform poorly in quantum physics, with fewer than 40% of students attaining mastery levels on standardised assessments (Gana, 2019; NCCE, 2018). More critically, retention of quantum concepts declines sharply in the weeks following instruction, undermining the long-term pedagogical competence of future teachers.

The dominant instructional paradigm in these institutions remains the Conventional Lecture Method (CLM)—a teacher-centred, expository approach characterised by didactic exposition, chalkboard explanations, and rote memorisation (Osuafor & Okigbo, 2019). Research has established that CLM is particularly ill-suited to the conceptual demands of quantum physics, which requires learners to construct mental models of phenomena that are fundamentally non-intuitive and invisible to direct observation (Zacharia & Anderson, 2015; Stadermann et al., 2019). The absence of experiential, visualisation-based learning opportunities leaves students unable to bridge the gap between abstract formalism and conceptual understanding. Computer-Assisted Instruction (CAI) has emerged internationally as a powerful pedagogical response to this challenge. Within the broad CAI landscape, Simulation-Based CAI is especially pertinent for physics education, as it enables learners to interact dynamically with virtual representations of phenomena that cannot be observed in conventional laboratory settings (Rutten et al., 2012; Smetana & Bell, 2018). By providing interactive simulations of wave functions, probability distributions, quantum tunnelling, and electron transitions, Simulation-CAI renders abstract quantum phenomena visually concrete, epistemically accessible, and cognitively engaging. Despite growing global evidence of CAI's effectiveness in science education, its application to quantum physics instruction at the Colleges of Education level in Nigeria remains empirically underexplored (Gana, 2019). This gap is particularly concerning given the dual pedagogical challenge these institutions face: students must simultaneously master quantum physics content and develop the instructional repertoire needed to teach it effectively. To address this gap, the present study investigates the effect of Simulation-CAI on the achievement and retention of NCE II Physics students in quantum physics in North Central Nigeria.

1.2 Statement of the Problem

Quantum Physics constitutes a critical component of modern scientific and technological advancement; however, students in Nigerian Colleges of Education, particularly within the North Central region, continue to demonstrate persistently low achievement in this area of Physics. Empirical reports have consistently indicated that less than 40% of students attain satisfactory mastery of quantum concepts, while knowledge retention declines considerably within a short period after instruction. This persistent underachievement raises serious concerns regarding the effectiveness of existing instructional approaches in fostering meaningful learning and conceptual understanding in quantum physics. The inherently abstract, highly mathematical, and conceptually demanding nature of quantum physics poses substantial learning difficulties for students. These challenges are further exacerbated by the continued reliance on conventional teacher-centred instructional methods, which often emphasize rote memorization rather than conceptual visualization, active engagement, and critical thinking. Consequently, many students experience difficulties in understanding fundamental quantum principles, interpreting microscopic phenomena, and relating theoretical concepts to real-world scientific applications.

In addition, inadequate laboratory facilities, insufficient instructional resources, overcrowded classrooms, and the limited integration of innovative technology-driven teaching strategies have continued to hinder effective teaching and learning of quantum physics in Colleges of Education. As a result, many Nigeria Certificate in Education (NCE) graduates, who are primarily trained to teach at the basic education level, often proceed to teach Physics at the senior secondary school level without adequate conceptual mastery, pedagogical confidence, or the necessary instructional competencies required for effective delivery of complex Physics concepts. Recent advancements in educational technology have introduced Simulation-based Computer-Assisted Instruction (Simulation-CAI) as a promising learner-centred instructional approach capable of transforming science education. Simulation-CAI provides interactive, visual, exploratory, and self-paced learning experiences that can facilitate deeper conceptual understanding and improve students' engagement with abstract scientific phenomena. Previous studies have reported positive effects of simulation-based learning on students' academic achievement, retention, motivation, and conceptual comprehension in science subjects. However, limited empirical evidence exists regarding its effectiveness in teaching quantum physics among students in Colleges of Education within North Central Nigeria.

It is against this backdrop that this study seeks to investigate the effect of Simulation-based Computer-Assisted Instruction on students' achievement and retention in quantum physics. The study is expected to provide empirical evidence that may contribute to improving instructional practices, strengthening curriculum implementation, and informing educational policies aimed at enhancing Physics education and producing more competent and effective future science educators in Nigeria.

Specifically, the study addresses four focused research questions and their corresponding null hypotheses:

1.3 Research Question

RQ1: What are the mean achievement scores of NCE II students taught quantum physics using Simulation-CAI and those taught using the Conventional Lecture Method?

RQ2: What are the mean achievement scores of male and female NCE II students taught quantum physics using Simulation-CAI?

RQ3: What are the mean retention scores of NCE II students taught quantum physics using Simulation-CAI and those taught using the Conventional Lecture Method?

RQ4: What are the mean retention scores of male and female NCE II students taught quantum physics using Simulation-CAI?

1.3 Hypotheses

Ho_1: There is no significant difference in the mean achievement scores of NCE II students taught quantum physics using Simulation-CAI and those taught with the Conventional Lecture Method.

Ho_2: There is no significant difference in the mean achievement scores of male and female NCE II students when taught quantum physics using Simulation-CAI.

Ho_3: There is no significant difference in the mean retention scores of NCE II students taught quantum physics using Simulation-CAI and CLM.

Ho_4: There is no significant difference in the mean retention scores of male and female NCE II students taught quantum physics using Simulation-CAI.

The paper proceeds as follows: Section 2 reviews the theoretical and empirical literature; Section 3 describes the methodology; Section 4 presents and analyses the results; Section 5 discusses the findings in relation to extant literature; and Section 6 presents conclusions, implications, and directions for future research.

2. LITERATURE REVIEW

2.1 Quantum Physics and the Pedagogical Challenge

Quantum physics occupies a unique epistemological position within the natural sciences: its foundational principles—wave-particle duality, superposition, non-locality, and probabilistic determinism—challenge classical intuitions in ways that render conventional instructional approaches fundamentally inadequate (Levrini & Fantini, 2019; Hoehn & Finkelstein, 2018). Unlike classical mechanics, where physical systems can be modelled through everyday analogies, quantum phenomena operate at scales and in regimes for which no sensory experience exists. This creates what Krijtenburg-Lewerissa et al. (2019) describe as an 'ontological gap' between students' intuitive frameworks and the formal conceptual structure of quantum theory. Research conducted across diverse educational contexts documents consistent patterns of conceptual difficulty among quantum physics learners: students frequently confuse probabilistic and deterministic interpretations, misattribute classical trajectories to quantum particles, and struggle to operationalise the uncertainty principle beyond its mathematical formulation (Stadermann et al., 2019). In the Nigerian College of Education context, these challenges are compounded by overcrowded classrooms, inadequate laboratory infrastructure, and limited access to advanced instructional resources, creating conditions under which conceptual development is particularly constrained (Gana, 2019; Osuafor & Okigbo, 2019).

2.2 Simulation-Based Computer-Assisted Instruction

Simulation-Based CAI is distinguished from other forms of technology-enhanced learning by its emphasis on dynamic, interactive modelling of complex or unobservable phenomena (Clark & Mayer, 2016). In physics education, simulation environments allow learners to manipulate variables, observe system responses, and iteratively test hypotheses within a virtual experimental context—thereby supporting active, inquiry-based learning (de Jong & van Joolingen, 1998). This experiential dimension is particularly consequential for quantum physics, where the phenomena of interest—electron probability distributions, quantum tunnelling through potential barriers, and superposition collapse upon measurement—cannot be demonstrated through conventional laboratory means (Finkelstein et al., 2005). A comprehensive meta-analysis by Schmid et al. (2014) involving 224 independent effect sizes confirmed that technology-enhanced instruction, including simulation-based approaches, produced significantly superior learning outcomes compared to conventional methods across postsecondary science disciplines. Rutten et al. (2012), in a systematic review of 50 studies, found consistent evidence that computer simulations enhance conceptual understanding and promote deeper cognitive engagement in science education. Smetana and Bell (2018) further demonstrated that interactive simulations are particularly effective when they embed immediate corrective feedback, support multiple representations of the same concept, and permit learner control over exploration—features directly embodied in the Simulation-CAI package developed for the present study.

2.3 Achievement and Retention in CAI-Mediated Physics Learning

Empirical studies across multiple contexts corroborate the potential of CAI to enhance both achievement and retention in physics. Adolphus and Omeodu (2020) found that students taught atomic and nuclear physics through CAI significantly outperformed those taught through the lecture method (mean achievement: 60.5 vs. 44.1). Suleman et al. (2017) similarly reported significant advantages in both achievement and retention for secondary physics students in a CAI condition compared to conventional instruction, two weeks post-intervention. Nwanne and Agommuoh (2017) reported comparable findings for Imo State senior secondary students, while Usman and Jilang (2018) demonstrated significant CAI-mediated achievement gains in Plateau State. In the retential domain, Egbodo (2016) found that students exposed to CAI retained Basic Science concepts significantly better than their conventionally taught peers, with retention differences remaining significant at $\alpha = .05$. Collectively, this body of evidence suggests a robust and generalisable pattern: Simulation-CAI enhances physics learning outcomes relative to conventional instruction. However, the literature base specific to quantum physics at the Colleges of Education level in the North Central Nigerian context is thin (Gana, 2019), and studies explicitly examining the differential impact of Simulation-CAI on immediate achievement versus delayed retention in this context are notably absent. The present study directly addresses this gap.

2.4 Theoretical Framework

The study is anchored theoretically in two complementary frameworks. First, Mayer's Cognitive Theory of Multimedia Learning (CTML; Mayer, 2022) provides the instructional design foundation. CTML posits that deep learning occurs when verbal and pictorial information are processed simultaneously through separate but coordinated cognitive channels, and that effective multimedia instruction reduces extraneous cognitive load while maximising generative processing. The interactive simulations in the Simulation-CAI package operationalise the multimedia, spatial contiguity, and modality principles of CTML, providing dynamic visual representations of quantum phenomena alongside explanatory narration and text. Second, the Feedback and Reinforcement Theory of Hattie and Timperley (2018) informs the study's conceptualisation of retention. Hattie and Timperley's synthesis of over 500,000 effect sizes identified feedback as among the most influential factors in educational achievement, particularly when it is immediate, specific, and targeted at the process or self-regulation levels. The Simulation-CAI package embeds immediate corrective feedback following each interaction, directly aligning with this theoretical imperative and providing a mechanistic explanation for why Simulation-CAI may produce superior retention over time.

3. METHODOLOGY

3.1 Research Design

A quasi-experimental pretest–posttest–post-posttest non-equivalent control group design was employed. This design was selected for its suitability in examining causal relationships in naturalistic educational settings where full random assignment of students is not feasible (Mason et al., 2015). The design enabled the study to assess immediate learning effects (pretest to posttest) and delayed retention (posttest to post-posttest retention test), thereby capturing both the short-term and longer-term consequences of the instructional treatment.

Table 1 Research Design Schema

Group	Pretest	Treatment	Posttest (Achievement)	Post-Posttest (Retention)
Experimental (Simulation-CAI)	O_1	X (Simulation-CAI)	O_2	O_3
Control (Conventional Lecture)	O_1	— (No treatment)	O_2	O_3

Note. O_1 = Pretest; O_2 = Posttest (immediately post-treatment); O_3 = Post-posttest retention test (2 weeks after O_2); X = Simulation-CAI treatment; — = No treatment (Conventional Lecture Method).

3.2 Participants and Sampling

The target population comprised all 441 NCE II Physics students enrolled across fourteen Colleges of Education in the North Central Zone of Nigeria during the 2024/2025 academic session (260 male; 181 female), as documented in the National Commission for Colleges of Education (NCCE) 2024 annual report. From this population, a sample of 236 NCE II Physics students (139 male, 97 female) was drawn from six purposively selected State Colleges of Education possessing functional ICT infrastructure and adequate computing facilities. Purposive sampling was employed at the institutional level to ensure ecological validity of the Simulation-CAI intervention—only colleges with stable power supply, functioning computer laboratories, and a sufficient number of computers for student use were eligible. At the class level, intact NCE II Physics classes were identified and randomly assigned: three colleges were allocated to the Simulation-CAI experimental condition (n = 113) and three to the Conventional Lecture Method control condition (n = 123). This two-stage procedure balanced ecological validity with internal validity considerations.

Table 2 Distribution of Sample by Experimental and Control Groups

Condition	**College**	**Code**	**N**
Experimental (Simulation-CAI)	College of Education Kabba	KAT	38
	College of Education Akwanga	AKW	40
	College of Education Oro	ORO	35
Experimental Subtotal			113
Control (CLM)	College of Education Gindiri	GIN	36
	College of Education Ankpa	ANK	42
	College of Education Minna	MIN	45
Control Subtotal			123
Total Sample			236

Note. CLM = Conventional Lecture Method. All colleges are State-owned institutions within the North Central Zone of Nigeria.

3.3 Instructional Intervention

The Quantum Physics Computer-Assisted Instruction Package (QPCAIP) was developed specifically for this study using simulation technology. The package was structured around four content units aligned with the NCCE minimum standard NCE II physics curriculum: (1) wave-particle duality and the double-slit experiment; (2) quantum states and superposition; (3) energy quantisation and Bohr's atomic model; and (4) Heisenberg's uncertainty principle and quantum tunnelling. Each unit incorporated dynamic visual simulations, interactive tutorials enabling student manipulation of key variables, multiple-choice questions with immediate corrective feedback, and self-paced progression mechanisms. The intervention was administered over four weeks, with experimental group students engaging with the QPCAIP on classroom computers. Control group students received instruction on the same content topics using the Conventional Lecture Method—characterised by chalkboard explanations, verbal exposition, and textbook-based exercises—without access to any computer-based resources. All lecturers were provided with standardised lesson plans and underwent structured training to ensure fidelity of implementation across conditions.

3.4 Instruments

Two instruments were developed and validated for data collection. The Quantum Physics Achievement Test (QPAT) consisted of 30 multiple-choice items with four options each, measuring students' mastery of quantum physics content aligned with Bloom's cognitive taxonomy. The instrument covered four content domains: Quantum Theory and Photons (30%), Atomic Models and Quantum Numbers (30%), Wave-Particle Duality and Electron Behaviour (20%), and Modern Quantum Applications (20%). The QPAT was administered as both pretest and posttest. The Quantum Physics Retention Test (QPRT) comprised 30 parallel items drawn from the same content domains, presented in an alternative sequence to minimise recall bias. The QPRT was administered as a post-posttest two weeks after the posttest to assess delayed knowledge retention. Both instruments underwent rigorous face and content validation by a panel of three quantum physics experts from two institutions, who evaluated scope and coverage, content relevance, item clarity, and alignment with study objectives. Reliability was established through pilot testing with 30 comparable NCE II students external to the study sample, yielding Kuder-Richardson

21 (KR-21) reliability coefficients of 0.88 for the QPAT and 0.84 for the QPRT—both indicating strong internal consistency.

Table 3 Summary of Research Instruments

Instrument	Items	Format	Purpose	Reliability (KR-21)	Administration Point
QPAT	30	4-option MCQ	Achievement measurement	0.88	Pretest & Posttest
QPRT	30	4-option MCQ	Retention measurement	0.84	Post-posttest (2 weeks after posttest)

Note. MCQ = Multiple-choice questions; KR-21 = Kuder-Richardson Formula 21. Each correct response scored 1 mark; total raw scores converted to percentage scores for analysis.

3.5 Data Analysis

Data were analysed using two complementary statistical approaches. Descriptive statistics—means and standard deviations—were computed to characterise group performance on each measurement occasion. Inferential testing employed Analysis of Covariance (ANCOVA) at $\alpha = .05$, with pretest scores as the covariate for achievement hypotheses (controlling initial knowledge equivalence) and posttest scores as the covariate for retention hypotheses (isolating retention gains from immediate achievement). Effect sizes were reported as partial eta squared (η^2), interpreted according to conventional benchmarks: $\eta^2 = .01$ (small), .06 (medium), .14 (large). All analyses were conducted using SPSS Version 25.

4. RESULTS

4.1 RQ1 and Ho1: Achievement by Instructional Method

RQ1 enquired about the mean achievement scores of NCE II students in quantum physics across the two instructional conditions. Table 4 presents the descriptive statistics. Both groups entered the study with near-identical pretest means (EG: M = 21.32, SD = 1.919; CG: M = 21.37, SD = 2.245), confirming pre-intervention equivalence. Following the four-week treatment, both groups recorded marginal posttest improvements: EG (M = 21.70, SD = 0.865) and CG (M = 21.64, SD = 0.679). The experimental group's posttest mean exceeded that of the control group by 0.06 marks—a negligible practical difference.

Table 4 Descriptive Statistics for Achievement by Instructional Group (RQ1)

Group	n	Pretest M (SD)	Posttest M (SD)	Gain (Posttest – Pretest)
Experimental (Simulation-CAI)	113	21.32 (1.919)	21.70 (0.865)	+0.38
Control (CLM)	123	21.37 (2.245)	21.64 (0.679)	+0.27

Note. M = Mean; SD = Standard Deviation. Scores represent percentage-converted raw totals out of 30 items.

Ho1 posited no significant difference in achievement between Simulation-CAI and CLM groups. The ANCOVA result (Table 5), with pretest as covariate, yielded $F(1, 233) = 0.306$, $p = .581$, $\eta^2 = .001$. The null hypothesis was therefore retained. Simulation-CAI did not produce a statistically significant advantage over conventional instruction in immediate posttest achievement. The model explained less than 0.5% of the variance in posttest scores ($R^2 = .004$, adjusted $R^2 = -.005$), and the pretest covariate itself was not a significant predictor of posttest performance ($F = 0.569$, $p = .452$).

Table 5 ANCOVA Results for Achievement by Instructional Group, Controlling for Pretest (Ho1)

Source	**Type III SS**	**df**	**MS**	**F**	**p**	**η²**
Corrected Model	0.531	2	0.266	0.443	.643	.004
Intercept	1086.726	1	1086.726	1812.646	<.001	.886
Pretest (Covariate)	0.341	1	0.341	0.569	.452	.002
Group (Sim-CAI vs CLM)	0.184	1	0.184	0.306	.581	.001
Error	139.689	233	0.600	—	—	—
Total	110958.000	236	—	—	—	—

Note. SS = Sum of Squares; MS = Mean Square. Dependent variable: Posttest Achievement Score. Covariate: Pretest Score. α = .05.

4.2 RQ2 and Ho2: Achievement by Gender Within the Simulation-CAI Group

RQ2 examined achievement score differences between male and female students within the experimental group (n = 113). Table 6 presents the descriptive data. Male students recorded pretest and posttest means of 21.44 (SD = 1.781) and 21.74 (SD = 0.847), respectively. Female students recorded corresponding means of 21.15 (SD = 2.106) and 21.64 (SD = 0.895). Both genders demonstrated marginal posttest gains, with males recording a marginally higher posttest mean by 0.10 marks.

Table 6 Descriptive Statistics for Achievement by Gender Within the Simulation-CAI Group (RQ2)

Gender	**N**	**Pretest M (SD)**	**Posttest M (SD)**	**Gain**
Male	66	21.44 (1.781)	21.74 (0.847)	+0.30
Female	47	21.15 (2.106)	21.64 (0.895)	+0.49

Note. Data presented for the Simulation-CAI experimental group only (n = 113).

Ho2 posited no significant gender difference in achievement within the Simulation-CAI group. ANCOVA with pretest as covariate (Table 7) yielded $F(1, 110) = 0.385$, $p = .536$, $\eta^2 = .003$. The null hypothesis was retained. The pretest covariate was non-significant ($F = 0.003$, $p = .955$), and the overall model was weak ($R^2 = .004$, adjusted $R^2 = -.015$), confirming that gender did not meaningfully differentiate achievement outcomes within the Simulation-CAI condition.

Table 7 ANCOVA Results for Achievement by Gender (Simulation-CAI Group), Controlling for Pretest (Ho2)

Source	**Type III SS**	**df**	**MS**	**F**	**p**	**η²**
Corrected Model	0.300	2	0.150	0.198	.821	.004
Intercept	420.122	1	420.122	553.655	<.001	.834
Pretest (Covariate)	0.002	1	0.002	0.003	.955	.000
Gender (within EG)	0.292	1	0.292	0.385	.536	.003
Error	83.470	110	0.759	—	—	—
Total	53290.000	113	—	—	—	—

Note. EG = Experimental Group (Simulation-CAI). Dependent variable: Posttest Achievement Score. Covariate: Pretest Score. α = .05.

4.3 RQ3 and Ho3: Retention by Instructional Method

RQ3 examined mean retention scores two weeks after the posttest. Table 8 reveals a substantively meaningful pattern: the experimental group's mean retention score (M = 21.85, SD = 0.899) exceeded its own posttest mean by 0.15 marks, whereas the control group's retention mean (M = 20.91, SD = 3.375) declined by 0.73 marks relative to its posttest. The control group's substantially elevated retention standard deviation (3.375 vs. 0.899) further indicates markedly greater inter-individual variability in knowledge maintenance under conventional instruction.

Table 8 Descriptive Statistics for Retention by Instructional Group (RQ3)

Group	N	Posttest M (SD)	Retention M (SD)	Change (Retention – Posttest)
Experimental (Simulation-CAI)	113	21.70 (0.865)	21.85 (0.899)	+0.15
Control (CLM)	123	21.64 (0.679)	20.91 (3.375)	−0.73

Note. Retention test administered two weeks after the posttest. Positive change values indicate knowledge maintenance or gain; negative values indicate knowledge decay.

Ho3 posited no significant difference in retention between instructional conditions. The ANCOVA (Table 9), controlling for posttest scores, yielded F(1, 233) = 8.421, p = .004, η^2 = .035. The null hypothesis was rejected. Simulation-CAI produced significantly superior retention compared to conventional instruction. The effect size (η^2 = .035) represents a small-to-moderate practical effect, indicating that instructional method accounted for approximately 3.5% of the variance in retention scores—a meaningful magnitude in educational intervention research. The corrected model was statistically significant overall (F = 4.650, p = .010), explaining approximately 3.8% of variance in retention.

Table 9 ANCOVA Results for Retention by Instructional Group, Controlling for Posttest (Ho3)

Source	Type III SS	df	MS	F	p	η^2
Corrected Model	58.812	2	29.406	4.650	.010	.038
Intercept	204.193	1	204.193	32.287	<.001	.122
Posttest (Covariate)	6.885	1	6.885	1.089	.298	.005
Group (Sim-CAI vs CLM)	53.258	1	53.258	8.421	.004*	.035
Error	1473.574	233	6.324	—	—	—
Total	109209.000	236	—	—	—	—

Note. Dependent variable: Retention Score. Covariate: Posttest Score. α = .05. *Statistically significant at p < .05.

4.4 RQ4 and Ho4: Retention by Gender Within the Simulation-CAI Group

RQ4 examined retention differences between male and female students within the Simulation-CAI group. Table 10 presents the descriptive data. Male students maintained identical posttest and retention means (M = 21.74, SD = 0.615 at retention), indicating perfect knowledge stability over the two-week interval. Female students demonstrated a marginally higher retention mean (M = 22.00, SD = 1.180) compared to their posttest (M = 21.64), representing a slight improvement. Notably, the lower standard deviation for males at retention (0.615) compared to females (1.180) indicates greater score homogeneity among males.

Table 10 Descriptive Statistics for Retention by Gender Within the Simulation-CAI Group (RQ4)

Gender	n	Posttest M (SD)	Retention M (SD)	Change
Male	66	21.74 (0.847)	21.74 (0.615)	0.00
Female	47	21.64 (0.895)	22.00 (1.180)	+0.36

Note. Data presented for the Simulation-CAI experimental group only (n = 113).

Ho4 posited no significant gender difference in retention within the Simulation-CAI group. ANCOVA with posttest as covariate (Table 11) yielded F(1, 110) = 2.441, $p = .121$, $\eta^2 = .022$. The null hypothesis was retained. Gender did not significantly predict retention performance within the Simulation-CAI condition. The posttest covariate was also non-significant (F = 0.871, $p = .353$), and the model explained only 2.8% of variance in retention ($R^2 = .028$, adjusted $R^2 = .010$).

Table 11 ANCOVA Results for Retention by Gender (Simulation-CAI Group), Controlling for Posttest (Ho4)

Source	Type III SS	df	MS	F	p	η²
Corrected Model	2.517	2	1.259	1.575	.212	.028
Intercept	70.083	1	70.083	87.678	<.001	.444
Posttest (Covariate)	0.696	1	0.696	0.871	.353	.008
Gender (within EG)	1.951	1	1.951	2.441	.121	.022
Error	87.925	110	0.799	—	—	—
Total	54037.000	113	—	—	—	—

Note. EG = Experimental Group (Simulation-CAI). Dependent variable: Retention Score. Covariate: Posttest Score. α = .05.

Summary of Hypothesis Testing Outcomes

Ho1 (Achievement — Method): RETAINED — F(1,233) = 0.306, $p = .581$, $\eta^2 = .001$ (no significant difference)

Ho2 (Achievement — Gender within Sim-CAI): RETAINED — F(1,110) = 0.385, $p = .536$, $\eta^2 = .003$ (no significant difference)

Ho3 (Retention — Method): REJECTED ✓ — F(1,233) = 8.421, $p = .004$, $\eta^2 = .035$ (Sim-CAI significantly superior)

Ho4 (Retention — Gender within Sim-CAI): RETAINED — F(1,110) = 2.441, $p = .121$, $\eta^2 = .022$ (no significant difference)

5. DISCUSSION

5.1 The Achievement Paradox: Why Simulation-CAI Did Not Significantly Outperform Conventional Instruction

The finding that Simulation-CAI did not produce statistically significantly higher immediate achievement scores than the Conventional Lecture Method (F = 0.306, $p = .581$) warrants careful theoretical and empirical interrogation, particularly given the broader literature's generally favourable assessment of CAI-mediated learning. Several inter-related explanations are proposed. First, the instrument-treatment alignment hypothesis merits consideration. The QPAT comprised primarily recognition-level multiple-choice items assessing declarative knowledge—item types for which lecture-based instruction, with its emphasis on definitional and propositional content, may be comparably effective to simulation-based approaches. Simulation-CAI, by contrast, is theoretically optimised for conceptual understanding, mental model construction, and the ability to apply quantum principles in novel configurational contexts—competencies not fully captured by a 30-item MCQ instrument (Mayer, 2022; Smetana & Bell, 2018). This interpretation aligns with Finkelstein et al.'s (2005) observation that simulation-based advantages are most pronounced on assessments requiring conceptual transfer rather than factual recall. Second, the ceiling effect must be acknowledged. Both groups entered the study with near-identical, relatively high pretest means (EG: 21.32/30; CG: 21.37/30—corresponding to approximately 71%), which substantially constrained the potential posttest improvement attainable by either group. Under ceiling conditions, discriminating between instructional methods on immediate post-test measures is inherently difficult (Levrini & Fantini, 2019). The compression of posttest standard deviations (EG: 0.865; CG: 0.679 vs pretest SDs of 1.919 and 2.245 respectively) corroborates this interpretation. Third, temporal factors are relevant. The four-week intervention may have been insufficient for Simulation-CAI's distinctive advantages—particularly its capacity to support iterative, self-paced knowledge construction—to manifest fully in immediate posttest performance. Makransky et al.'s (2016) work on simulation-based laboratory preparation similarly found that simulation advantages over conventional approaches emerged more clearly over extended timeframes. This temporal dynamic becomes central to understanding the retention findings discussed below. These considerations do not negate the practical value of Simulation-CAI; rather, they underscore the importance of aligning assessment instruments with the specific cognitive processes that technology-enhanced pedagogies are designed to cultivate, a methodological imperative well-established in the science education research literature (Schmid et al., 2014).

5.2 The Retention Advantage: Simulation-CAI as a Mechanism for Durable Learning

The most theoretically consequential finding of this study is the significant and practically meaningful retention advantage yielded by Simulation-CAI over conventional instruction ($F = 8.421$, $p = .004$, $\eta^2 = .035$). Two weeks' post-instruction, experimental group students not only maintained but marginally improved their mean performance (M: 21.70 → 21.85), whereas control group students exhibited a statistically significant knowledge decay, with mean scores declining from 21.64 to 20.91 and standard deviations expanding dramatically from 0.679 to 3.375. This divergent pattern—stability and slight improvement in the Simulation-CAI group versus decline and increased variability in the CLM group—constitutes robust evidence for Simulation-CAI's capacity to promote durable knowledge encoding. This finding is theoretically interpretable through both frameworks anchoring the study. Within Mayer's CTML (2022), the interactive simulations in the Simulation-CAI package enabled learners to construct dual-coded mental models by simultaneously processing dynamic visual representations and verbal explanations of quantum phenomena. Dual-coded representations are inherently more robust and retrievable than single-code (verbal-only) encodings, because they provide multiple retrieval cues that can be independently activated during recall (Mayer & Chandler, 2016). The conventional lecture, relying predominantly on verbal-symbolic representation, generates less redundancy in encoding and is correspondingly more susceptible to forgetting. Within Hattie and Timperley's (2018) framework, the Simulation-CAI package's embedded immediate feedback mechanism—which detected incorrect responses and provided targeted corrective information at the point of error—directly operationalised the most effective form of task-level and process-level feedback. This iterative error-correction cycle enabled students to consolidate accurate conceptual representations during learning rather than encoding incorrect or incomplete models, which would require effortful remediation later. The control group's exposure to lecture-based instruction, with feedback deferred to end-of-lesson quizzes, provided far fewer opportunities for real-time conceptual correction.

The retention finding resonates strongly with multiple convergent empirical investigations. Suleman et al. (2017) documented significant CAI-mediated retention advantages in secondary physics, with CAI students performing substantially better on delayed retention tests. Egbodo (2016) reported parallel findings in Basic Science, where CAI-exposed students retained concepts significantly better than CLM-exposed peers over comparable intervals. Onyema and Olele (2020), studying physics retention in Federal Colleges of Education in South-Eastern Nigeria, similarly found that digitally mediated instruction significantly outperformed conventional approaches in knowledge maintenance, though their study employed a blended format rather than simulation-specific CAI. The convergence of these findings across disciplines, student populations, and regional contexts strengthens the generalisability of the present study's conclusion. The substantially elevated control group retention standard deviation (3.375 vs. 0.899 for the experimental group) warrants additional comment. This divergence suggests that conventional lecture instruction produces highly heterogeneous knowledge retention: some students retain well, but many experience pronounced forgetting. Simulation-CAI, by contrast, appears to function as an equaliser—supporting consistent knowledge maintenance across learners with varying prior knowledge levels, attentional capacities, and metacognitive skills. This homogenising effect may reflect the self-pacing affordances of the Simulation-CAI package, which allowed students who needed additional time with difficult concepts to revisit simulations without the time constraints imposed by lecture-paced instruction.

5.3 Gender-Neutrality of Simulation-CAI Effects

The non-significant gender effects on achievement (Ho2: F = 0.385, p = .536) and retention (Ho4: F = 2.441, p = .121) within the Simulation-CAI group represent an important secondary finding. Despite female students showing a marginally higher retention improvement (+0.36 marks) compared to male students (stable at 21.74), the difference did not reach statistical significance. This gender neutrality of Simulation-CAI's effects aligns with Egbodo (2016), Onyema and Olele (2020), and Agwagah et al. (2019), all of whom reported non-significant gender differences on achievement and retention outcomes in CAI conditions across Nigerian contexts. It suggests that Simulation-CAI's interactive, self-paced, and visualisation-rich environment creates equitable learning conditions that transcend the gender-differentiated performance patterns documented in conventionally taught physics classrooms (Gambari et al., 2014). For teacher education institutions striving to produce equally competent male and female physics teachers, this gender-equitable characteristic of Simulation-CAI represents a significant pedagogical asset.

6. CONCLUSIONS AND IMPLICATIONS

6.1 Conclusions

This study investigated the effects of Simulation-Based Computer-Assisted Instruction on the achievement and retention of NCE II Physics students in quantum physics in North Central Nigeria. The empirical evidence generated leads to four principal conclusions:

1. Simulation-CAI does not significantly outperform Conventional Lecture instruction in immediate posttest achievement of quantum physics concepts, likely due to ceiling effects, instrument-treatment misalignment, and the insufficient duration of the intervention for simulation-specific advantages to manifest in declarative knowledge measures.
2. Simulation-CAI produces statistically significant and practically meaningful advantages in delayed knowledge retention compared to conventional instruction, with experimental group students maintaining or improving their performance over a two-week interval while control group performance declined substantially.
3. Both achievement and retention outcomes within the Simulation-CAI condition are gender-neutral: male and female students perform comparably under Simulation-CAI, indicating that the technology creates equitable learning environments.
4. The standard deviation patterns in retention data suggest that Simulation-CAI promotes more homogeneous knowledge maintenance across learners, functioning as a pedagogical equaliser that mitigates the high inter-individual variability in knowledge decay characteristic of conventional lecture-based instruction.

6.2 Theoretical Contributions

The study makes three original theoretical contributions. First, it provides empirical support for a differentiated view of Simulation-CAI's impact: the technology exerts its primary advantage not on immediate achievement but on delayed retention, suggesting that simulation-based learning operates primarily through deep encoding mechanisms (dual-coding, elaborative processing, and iterative feedback) that produce durable rather than merely immediate learning gains. This nuances prevailing meta-analytic conclusions, which have largely aggregated immediate and delayed outcome measures (Schmid et al., 2014; Rutten et al., 2012). Second, the study extends Mayer's CTML (2022) to the domain of quantum physics teacher education within a low-resource African context, demonstrating that the theory's predictions regarding multimedia learning advantage hold even when students have limited prior experience with simulation-based tools and operate in contexts characterised by infrastructural constraints. Third, the study contributes novel evidence to the ongoing discourse on gender equity in STEM education by demonstrating that Simulation-CAI operates as a gender-neutral instructional strategy—a finding with significant implications for efforts to close the gender gap in physics teacher preparation.

6.3 Practical Implications

For physics educators and curriculum planners in Nigerian Colleges of Education and analogous institutions across sub-Saharan Africa, the retention finding carries immediate practical significance. Given that the primary goal of teacher education is long-term professional competence—not merely performance on immediate assessments—the superior retention afforded by Simulation-CAI argues strongly for its systematic integration into physics teacher preparation curricula. Future physics educators who retain quantum concepts more durably will be better equipped to teach these topics confidently and accurately to their own students, producing downstream benefits for secondary science education. For institutional leaders and policymakers, the study underscores the strategic value of investing in digital learning infrastructure. Functional computer laboratories, stable power supply, and appropriate simulation software represent high-return investments given the documented retention benefits. The National Commission for Colleges of Education (NCCE) should consider revising the NCE minimum standards to mandate the integration of simulation-based tools in quantum physics instruction. Professional development programmes, including workshops and in-service training, should be organised to build physics lecturers' competence and confidence in deploying Simulation-CAI.

6.4 Limitations and Future Directions

Several limitations should inform the interpretation and application of the findings. The four-week intervention duration may have constrained the full expression of Simulation-CAI's achievement benefits; future studies should examine longer interventions and assess learning at multiple time points to map the trajectory of knowledge acquisition and retention. The sample, though methodologically sound, was restricted to six State Colleges of Education in one geopolitical zone; generalisability to Federal institutions, other zones, and other Nigerian educational contexts awaits confirmation. The study's retention interval (two weeks) is methodologically defensible but relatively short for claims about long-term memory consolidation. Future research should extend retention assessments to 4, 8, and 16 weeks post-instruction to characterise the full forgetting curve under each condition. Additionally, future investigations should employ conceptual assessment instruments—rather than purely declarative MCQ formats—to more sensitively capture Simulation-CAI's theorised advantages in conceptual understanding and application. Qualitative approaches, including think-aloud protocols and cognitive interviews, would enrich understanding of how students process and represent quantum phenomena during simulation-based learning.

Comparative studies examining Simulation-CAI against other technology-enhanced modalities—augmented reality, gamified learning platforms, and virtual reality—in quantum physics education contexts would further advance the field. Finally, longitudinal investigations tracking the pedagogical competence of NCE graduates who received Simulation-CAI training into their professional teaching careers would provide the most ecologically valid evidence of this technology's ultimate educational impact.

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