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# Instructional Method, Gender and Their Interaction Effects on Achievement and Retention in Quantum Physics: Evidence from Nigerian Colleges of Education

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## *Abstract*

The interplay between instructional method and learner gender in technology-enhanced physics education constitutes a consequential yet underexplored area of inquiry, particularly within the domain of quantum physics—a field characterised by high conceptual abstraction, documented gender-differentiated engagement patterns, and critical importance for science teacher preparation. This quasi-experimental study investigated the interaction effects of instructional method (Simulation-Based Computer-Assisted Instruction [Simulation-CAI] vs. Conventional Lecture Method [CLM]) and gender on both immediate achievement and delayed retention in quantum physics among Nigeria Certificate in Education (NCE II) students in North Central Nigeria. Underpinned by Mayer's Cognitive Theory of Multimedia Learning (CTML) and Bem's Gender Schema Theory, the study employed a pretest–posttest–post-posttest non-equivalent control group design with a total sample of 236 NCE II Physics students (139 male, 97 female) drawn from six purposively selected Colleges of Education. Three institutions were assigned to the Simulation-CAI experimental condition (n = 113; 66 male, 47 female) and three to the CLM control condition (n = 123; 73 male, 50 female). Two psychometrically validated instruments—the Quantum Physics Achievement Test (QPAT; KR-21 = 0.88) and the Quantum Physics Retention Test (QPRT; KR-21 = 0.84)—captured immediate and delayed learning outcomes respectively. Two-factor Analysis of Covariance (ANCOVA) was employed for all inferential analyses at $\alpha = .05$. Results revealed no statistically significant interaction between instructional method and

gender on achievement (Group × Gender: $F[1, 231] = 0.281$, $p = .596$, $\eta^2 = .001$) or on retention (Group × Gender: $F[1, 231] = 2.239$, $p = .136$, $\eta^2 = .010$). Critically, a significant main effect of instructional method on retention ($F[1, 231] = 9.827$, $p = .002$, $\eta^2 = .041$) confirmed Simulation-CAI's superiority in supporting durable knowledge maintenance across both genders. Descriptive data further revealed that female students in the CLM condition experienced severe retention decline ($\Delta = -1.18$; $SD = 4.500$) compared to their Simulation-CAI counterparts who marginally improved ($\Delta = +0.36$), suggesting that conventional instruction constitutes a differential retention risk for female physics students—a finding with significant gender equity implications. The absence of a significant interaction confirms that Simulation-CAI delivers gender-equitable learning outcomes, functioning as an inclusive and pedagogically superior strategy for quantum physics teacher education.

**Keywords:** gender interaction effects; Simulation-CAI; quantum physics; achievement; retention; Colleges of Education; Nigeria; STEM gender equity; multimedia learning; conventional lecture method

# Introduction

Gender equity in science, technology, engineering, and mathematics (STEM) education ranks among the most consequential and persistently contested challenges confronting educational systems worldwide. Within physics—a discipline historically characterised by male-dominated participation, performance patterns, and professional representation—the question of how instructional approach interacts with student gender to shape learning outcomes has attracted sustained scholarly attention (Gambari et al., 2014; Akinbobola & Afolabi, 2019; Voyer et al., 1995). The critical policy and research question is not merely whether male and female students perform differently in physics under conventional conditions, but whether the deliberate choice of instructional method can moderate, amplify, or entirely dissolve such differences—and, specifically, whether technology-enhanced pedagogies such as Simulation-Based Computer-Assisted Instruction (Simulation-CAI) can function as gender-equitable or gender-equalising forces in abstract physics domains where gender disparities have been most pronounced. Quantum physics represents precisely such a domain. It is foundational to modern scientific and technological civilisation—underpinning semiconductors, lasers, quantum computing, and precision measurement—yet it is simultaneously one of the most conceptually demanding and pedagogically challenging subjects in the physics curriculum. Its core principles (wave-particle duality, superposition, quantum tunnelling, energy quantisation, and the uncertainty principle) operate at scales and in theoretical registers that challenge classical intuition and resist conventional observational demonstration (Krijtenburg-Lewerissa et al., 2019; Stadermann et al.,

2019). In Nigerian Colleges of Education, where quantum physics is introduced at the NCE II level as a core component of physics teacher preparation, the pedagogical challenge is compounded by overcrowded classrooms, inadequate laboratory infrastructure, and the near-universal dominance of the Conventional Lecture Method (CLM)—a teacher-centred, expository approach ill-suited to the conceptual demands of quantum theory (Gana, 2019; Osuafor & Okigbo, 2019).

Simulation-CAI has emerged internationally as a theoretically grounded and empirically supported alternative. By enabling dynamic visual interaction with quantum phenomena that are otherwise imperceptible, Simulation-CAI supports dual-channel cognitive processing, self-paced conceptual exploration, and immediate corrective feedback—features directly aligned with principles of effective multimedia learning (Mayer, 2022). Yet a critically underexplored question remains: does Simulation-CAI benefit male and female physics learners equally, or does it interact with gender to produce differential achievement and retention outcomes? This question has direct implications for gender equity in STEM teacher education and for the design of inclusive digital learning environments. The present study directly addresses this gap. Reframing the doctoral thesis of Abdullahi (2025) with a focused gender-interaction analytical lens, this paper investigates the interaction effects of instructional method (Simulation-CAI vs. CLM) and gender on both immediate achievement and delayed retention in quantum physics among NCE II students in North Central Nigeria. Rather than treating gender as a background demographic variable, this study positions it as a theoretically central moderating factor whose interaction with instructional method constitutes the primary analytical focus. The study is guided by two research questions and their corresponding null hypotheses:

**RQ1:** What is the interaction effect of instructional method and gender on the achievement of NCE II students taught quantum physics?

**RQ2:** What is the interaction effect of instructional method and gender on the retention of NCE II students taught quantum physics?

**Ho1:** There is no significant interaction effect of instructional method and gender on students' achievement in quantum physics.

**Ho2:** There is no significant interaction effect of instructional method and gender on students' retention in quantum physics.

The paper proceeds as follows: Section 2 develops the theoretical and empirical foundation with a focused gender-interaction lens; Section 3 details the methodology; Section 4 presents results disaggregated by Group × Gender cells; Section 5 interprets the findings against theory and comparable empirical evidence; and Section 6 presents conclusions, theoretical contributions, and implications for policy and future research.

**Gender Differences in Physics Achievement: Patterns and Determinants**

The relationship between gender and physics achievement has produced a voluminous and contested literature. Internationally, meta-analyses of PISA and TIMSS data document a

tendency for male students to record higher mean scores in physics and integrated science tasks, though the magnitude of these differences varies considerably across national, cultural, and curricular contexts (Voyer et al., 1995; Gafor & Shilna, 2014). In the Nigerian context, Gambari et al. (2014) and Akinbobola and Afolabi (2019) reported significant male advantages in physics achievement under conventional lecture-based instruction, while Ariyo (2015) and Ibrahim (2017) found no significant gender differences—a discrepancy that points to the instructional method as a potential moderating variable rather than gender as a stable fixed factor. This contextual variability is theoretically important. If gender effects on physics achievement were biologically fixed, they would be consistent across instructional contexts. The fact that they are not suggests that they are produced and reproduced—or mitigated—through the specific pedagogical environments in which physics learning occurs (Uzoechi & Gimba, 2015). This repositions the question from 'do males and females differ in physics achievement?' to 'under what instructional conditions do gender differences emerge, persist, or disappear?'—a shift from descriptive to explanatory inquiry that places instructional method × gender interaction analysis at the methodological and theoretical centre.

**Gender, Technology, and CAI: The Interaction Hypothesis**

The hypothesis that computer-based instruction differentially affects male and female learners is grounded in documented gender differences in technology attitudes, computer self-efficacy, and spatial reasoning—all of which have been proposed as moderators of CAI effectiveness (Sax, 2001; Sung et al., 2016). Research conducted in the 1990s and early 2000s consistently documented male advantages in computer use frequency, gaming experience, and technology self-efficacy, leading to predictions that CAI would preferentially benefit male students by capitalising on these prior technology exposures. More recent evidence has substantially revised this picture. Gender gaps in computer access and basic digital literacy have narrowed markedly in most Sub-Saharan African contexts as smartphone penetration has increased (Sung et al., 2016). Moreover, the specific design of a CAI environment—its interactivity structure, feedback modality, pacing control, and social dimension—may matter more for gender-differential outcomes than computer use per se. Individual, self-paced tutorial CAI (such as the QPCAIP employed in the present study) is theoretically predicted to produce gender-neutral outcomes because it removes competitive, time-pressured, and socially evaluative dimensions of physics instruction that may disproportionately disadvantage female students under conventional lecture conditions (Zacharia & Olympiou, 2018).

Empirically, the picture remains heterogeneous. Nduati (2015), in Kenyan secondary chemistry, found that CAI produced larger achievement gains for male than female students. Julius et al. (2018), also in Kenya, reported the opposite—female students outperformed males under CAI in chemistry. In the Nigerian context, Egbodo (2016) and Agwagah et al. (2019) both found non-significant gender × method interactions under individual CAI in Basic Science and Mathematics respectively, while Onasanya et al. (2016) found gender moderation only under cooperative (not individual) CAI modalities. The present study adds to this

literature by examining the interaction specifically in quantum physics at the NCE level—a context, discipline, and educational level not previously addressed in the gender × CAI interaction literature.

**Gender Differences in Knowledge Retention Under Technology-Enhanced Instruction**

While the literature on gender × CAI interactions in immediate achievement is reasonably developed, the corresponding literature on delayed retention is substantially thinner. Retention—defined here as the ability to correctly recall and apply quantum physics knowledge two weeks after instruction—is arguably the more educationally consequential outcome for teacher preparation, as it approximates the durable professional knowledge that future physics teachers will need to draw upon throughout their careers. The few studies that have examined gender × method interactions on retention outcomes consistently report non-significant interactions but directionally interesting descriptive patterns (Egbodo, 2016; Onyema & Olele, 2020; Gana, 2019), suggesting that the question of differential retention under CAI is not settled. A critical observation from the available descriptive data is that female students under conventional lecture instruction appear to be particularly vulnerable to post-instruction knowledge decay—a pattern visible in the dramatic retention standard deviation differences across gender and method cells in the present dataset. This vulnerability is theoretically interpretable through Gender Schema Theory: lecture-based physics instruction, with its authority-centred pedagogy and masculine-coded subject matter, may activate suppressive gender schemata that impair long-term encoding and retrieval for female students, while leaving male students' retention relatively unaffected. Simulation-CAI, by redesigning the physics learning environment around self-directed exploration, individualised feedback, and visual-interactive engagement rather than didactic authority, may attenuate schema activation and thereby protect retention—particularly for female learners.

**Cognitive Theory of Multimedia Learning (CTML)**

Mayer's Cognitive Theory of Multimedia Learning (CTML; 2022) provides the instructional design foundation for predicting differential outcomes between Simulation-CAI and CLM conditions. CTML posits that meaningful learning occurs when learners simultaneously process related verbal and pictorial information through separate auditory-verbal and visual-pictorial channels, organise each representation into coherent mental models, and integrate the models with prior knowledge. The theory's individual differences principle predicts that multimedia learning advantages are strongest for learners with lower prior knowledge, higher spatial ability, and lower working-memory load—parameters that do not systematically favour one gender over the other when prior knowledge is equated at pretest. Accordingly, CTML predicts no significant gender × method interaction on immediate achievement when baseline knowledge is equivalent across gender groups—a prediction directly testable through the present study's two-factor design.

**Gender Schema Theory**

Bem's (1981) Gender Schema Theory offers the complementary lens for interpreting retention differences. The theory proposes that gender schemata—culturally acquired cognitive frameworks associating certain domains, activities, and competencies with masculinity or femininity—influence how individuals engage with, process, and persist in domain-specific learning. In physics, gender schemata have historically constructed the discipline as masculine, potentially suppressing female students' domain identification, self-efficacy, and intrinsic motivation under conventional instructional conditions (Archer et al., 2012; Hazari et al., 2010). These motivational and identity suppressions have downstream consequences for long-term knowledge retention: disengaged and identity-threatened learners are less likely to engage in the self-regulated consolidation activities (review, elaboration, retrieval practice) that support durable memory encoding. The theoretical synthesis of CTML and Gender Schema Theory generates a specific, testable prediction: Simulation-CAI, if designed with inclusive, self-paced, exploratory features that minimise schema-activating instructional dynamics, should produce no significant gender × method interaction on achievement (CTML prediction) while potentially attenuating the gender-differential vulnerability to retention decay observed under conventional lecture instruction (Gender Schema Theory prediction). The present study directly tests these integrated predictions.

**Positioning the Present Study**

The present study is positioned at the intersection of three underserved areas in the science education literature: (1) quantum physics education at the Colleges of Education level in Nigeria; (2) gender × CAI interaction effects in physics, as distinct from chemistry, mathematics, or biology; and (3) gender-differential retention outcomes under technology-enhanced versus conventional instruction. By employing a two-factor ANCOVA design with both achievement and retention as outcome variables, the study provides a more complete empirical picture of gender-differentiated learning trajectories under Simulation-CAI than any single-outcome or single-factor study could yield.

**Research Design**

A quasi-experimental pretest–posttest–post-posttest non-equivalent control group design was employed, augmented by a two-factor factorial analytic structure that positioned instructional method (Simulation-CAI vs. CLM) and gender (male vs. female) as the two independent variables. Three measurement occasions were incorporated: pretest ($O_1$, administered before the four-week intervention), posttest ($O_2$, administered immediately after the intervention), and post-posttest retention test ($O_3$, administered two weeks after $O_2$). This three-occasion design enabled the study to assess immediate achievement gains ($O_1 \rightarrow O_2$) and delayed retention ($O_2 \rightarrow O_3$) within a unified analytic framework, and the two-factor structure produced four theoretically and empirically distinct cells: Simulation-CAI × Male, Simulation-CAI × Female, CLM × Male, and CLM × Female.

**Table 1.** Two-Factor Design: Cell Composition by Method and Gender

| Factor | Level | Group | n (Male) | n (Female) | Cell Total |
|---|---|---|---|---|---|
| **Method** | Simulation-CAI (EG) | 3 Colleges | 66 | 47 | 113 |
| | CLM (CG) | 3 Colleges | 73 | 50 | 123 |
| Total | | | **139** | **97** | **236** |

**Note.** EG = Experimental Group (Simulation-CAI); CG = Control Group (CLM). Each college contributed one intact NCE II Physics class.

**Population, Sample, and Sampling Procedure**

The target population comprised all 441 NCE II Physics students (260 male, 181 female) enrolled in fourteen Colleges of Education across the North Central Zone of Nigeria during the 2024/2025 academic session (NCCE, 2024). From this population, a purposive sample of 236 students was drawn from six State Colleges of Education selected on the basis of three eligibility criteria: functional ICT infrastructure with sufficient networked computers for intact class deployment, stable electrical power supply, and adequate NCE II Physics enrollment. These criteria ensured ecological validity and methodological comparability of the Simulation-CAI intervention across sites. Three colleges were randomly assigned to the Simulation-CAI condition and three to the CLM condition, with intact classes forming the allocation units.

**Table 2.** Sample Distribution by Instructional Condition, College, and Gender

| Condition | College | Code | Male | Female | Total |
|---|---|---|---|---|---|
| **Experimental (Sim-CAI)** | COE Kabba | KAT | 22 | 16 | 38 |
| | COE Akwanga | AKW | 24 | 16 | 40 |
| | COE Oro | ORO | 20 | 15 | 35 |
| EG Subtotal | | | **66** | **47** | **113** |
| **Control (CLM)** | COE Gindiri | GIN | 21 | 15 | 36 |
| | COE Ankpa | ANK | 25 | 17 | 42 |
| | COE Minna | MIN | 27 | 18 | 45 |
| CG Subtotal | | | **73** | **50** | **123** |
| Grand Total | | | **139** | **97** | **236** |

**Note.** COE = College of Education. All institutions are State-owned within the North Central Geopolitical Zone. Gender composition was balanced across conditions: males constituted 58.4% (EG) and 59.3% (CG) of their respective groups.

**Instructional Intervention**

The Quantum Physics Computer-Assisted Instruction Package (QPCAIP) was purpose-built for this study using simulation technology. The package comprised four instructional units: (1) Wave-Particle Duality and the Double-Slit Experiment; (2) Quantum States and Superposition; (3) Energy Quantisation and Atomic Energy Levels; and (4) Heisenberg's

Uncertainty Principle and Quantum Tunnelling. Each unit incorporated dynamic visual simulations allowing variable manipulation, self-paced tutorial modules, multiple-choice embedded questions with immediate corrective feedback, and explanatory animations. The self-paced, individualised delivery mode was intentionally selected to minimise the competitive and socially evaluative dynamics of lecture-based instruction that may disproportionately disadvantage female students. Experimental group students engaged with the QPCAIP on individual laboratory computers over four weekly instructional sessions. Control group students received equivalent content via the Conventional Lecture Method—chalkboard exposition, verbal explanation, textbook exercises, and end-of-lesson oral review—without any computer access. All lecturers received standardised lesson plans and structured implementation training to ensure fidelity. Cross-contamination between groups was prevented by scheduling experimental and control sessions in different time slots and laboratory spaces.

**Instruments**

The Quantum Physics Achievement Test (QPAT) comprised 30 four-option multiple-choice items assessing quantum physics content across four domains: Quantum Theory and Photons (30%), Atomic Models and Quantum Numbers (30%), Wave-Particle Duality (20%), and Modern Quantum Applications (20%), distributed across Bloom's cognitive levels (Remember, Understand, Apply, Analyse). Administered at pretest and posttest, the QPAT yielded the immediate achievement measure. The Quantum Physics Retention Test (QPRT) comprised 30 parallel items in a reshuffled order and was administered two weeks post-posttest. Both instruments were validated by three quantum physics experts and pilot-tested on 30 comparable NCE II students, yielding KR-21 reliability coefficients of 0.88 (QPAT) and 0.84 (QPRT).

**Table 3.** Instruments: Summary of Psychometric Properties and Administration Schedule

| Instrument | Items | Domains | KR-21 | Administration | Outcome Measured |
|---|---|---|---|---|---|
| **QPAT** | 30 | Quantum Theory; Atomic Models; Wave-Particle Duality; Modern Applications | 0.88 | Pretest & Posttest | Immediate Achievement |
| **QPRT** | 30 | Same 4 domains; reshuffled item order | 0.84 | Post-posttest (2 wks after $O_2$) | Delayed Retention |

**Note.** KR-21 = Kuder-Richardson Formula 21. All raw scores converted to percentage equivalents prior to analysis. Items scored 1 (correct) or 0 (incorrect).

**Data Analysis**

The interaction hypotheses (Ho5 and Ho6) were tested using two-factor Analysis of Covariance (ANCOVA). For the achievement interaction (Ho5), pretest score served as the

covariate and the model included: Covariate (Pretest), Main Effect of Group (Simulation-CAI vs. CLM), Main Effect of Gender (Male vs. Female), and the Group × Gender interaction term as the focal predictor. For the retention interaction (Ho6), posttest score served as the covariate within the same factorial structure. The two-factor ANCOVA framework controls pre-existing group differences while decomposing outcome variance into components attributable to method, gender, and their interaction—enabling precise identification of the interaction effect independent of main effects.

Descriptive statistics (means and standard deviations) were computed for each of the four Group × Gender cells at each measurement occasion. Effect sizes were reported as partial eta squared ($\eta^2$), benchmarked against Cohen (1988): $\eta^2 = .01$ (small), .06 (medium), .14 (large). Post-hoc statistical power was estimated using G*Power 3.1 to contextualise any non-significant findings. Profile plots of estimated marginal means were generated to facilitate visual interpretation of interaction patterns. All analyses were conducted using IBM SPSS Statistics Version 25, with $\alpha = .05$.

**Descriptive Statistics for Achievement**

Table 4 presents the pretest and posttest achievement means for all four Group × Gender cells. Pre-intervention equivalence is confirmed across all cells, with pretest means ranging narrowly from 21.15 to 21.48—a spread of 0.33 marks across the four cells, indicating comparable baseline quantum physics knowledge irrespective of group or gender. Within the Simulation-CAI group, male students recorded a pretest-to-posttest gain of +0.30 marks (21.44 → 21.74), while female students gained +0.49 marks (21.15 → 21.64). Within the CLM group, male students gained +0.34 marks (21.30 → 21.64) and female students gained +0.16 marks (21.48 → 21.64). Two descriptive patterns are noteworthy. First, posttest standard deviations contracted markedly for all four cells (range: 0.663–0.895) relative to pretest (range: 1.515–2.639), indicating that both Simulation-CAI and CLM produced convergent performance following instruction. Second, male and female posttest means were identical within the CLM group (both 21.64), suggesting that conventional instruction produced perfect gender convergence in immediate achievement. In the Simulation-CAI group, a marginal male advantage persisted at posttest (21.74 vs. 21.64), though the difference of 0.10 marks is negligibly small in practical terms. Inferential testing determines whether this descriptive pattern constitutes a statistically meaningful interaction.

**Table 4.** Achievement Descriptive Statistics by Instructional Group and Gender (RQ5)

| Group | Gender | N | Pretest M | Pretest SD | Posttest M | Posttest SD | Gain (M) |
|---|---|---|---|---|---|---|---|
| **Experimental (Sim-CAI)** | Male | 66 | 21.44 | 1.781 | 21.74 | 0.847 | +0.30 |
| | Female | 47 | 21.15 | 2.106 | 21.64 | 0.895 | +0.49 |
| EG Subtotal | | **113** | **21.32** | 1.919 | **21.70** | 0.865 | **+0.38** |
| **Control (CLM)** | Male | 73 | 21.30 | 2.639 | 21.64 | 0.695 | +0.34 |

| Group | Gender | N | Pretest M | Pretest SD | Posttest M | Posttest SD | Gain (M) |
|---|---|---|---|---|---|---|---|
| | Female | 50 | 21.48 | 1.515 | 21.64 | 0.663 | +0.16 |
| CG Subtotal | | **123** | **21.37** | 2.245 | **21.64** | 0.679 | **+0.27** |

**Note.** M = Mean; SD = Standard Deviation; Gain = Posttest M − Pretest M. Scores are percentage-converted totals out of 30 items. EG = Experimental Group; CG = Control Group.

**Two-Factor ANCOVA for the Achievement Interaction (Ho5)**

Table 5 presents the two-factor ANCOVA for posttest achievement with pretest as covariate. The Group × Gender interaction term—the primary predictor for Ho5—yielded $F(1, 231) = 0.281$, $p = .596$, $\eta^2 = .001$. This result falls well below the $\alpha = .05$ significance threshold, and the associated effect size is negligibly small, accounting for less than 0.1% of variance in posttest achievement. Ho5 is therefore retained: the interaction effect of instructional method and gender on achievement in quantum physics is not statistically significant. The main effect of Group on achievement was also non-significant ($F[1, 231] = 0.205$, $p = .651$, $\eta^2 = .001$), as were the main effects of Gender ($F[1, 231] = 0.286$, $p = .593$, $\eta^2 = .001$) and the pretest covariate ($F[1, 231] = 0.617$, $p = .433$, $\eta^2 = .003$). The full corrected model explained only 0.6% of posttest variance ($R^2 = .006$, Adjusted $R^2 = -.011$), confirming that neither instructional method, gender, nor their interaction constituted meaningful predictors of immediate quantum physics achievement in this sample.

**Table 5.** Two-Factor ANCOVA: Interaction Effect of Method × Gender on Achievement (Ho5)

| Source | Type III SS | df | MS | F | p | $\eta^2$ | Decision |
|---|---|---|---|---|---|---|---|
| **Corrected Model** | 0.861 | 4 | 0.215 | 0.357 | .839 | .006 | — |
| **Intercept** | 1084.687 | 1 | 1084.687 | 1797.956 | <.001 | .886 | — |
| **Pretest (Covariate)** | 0.372 | 1 | 0.372 | 0.617 | .433 | .003 | — |
| **Group (Method)** | 0.124 | 1 | 0.124 | 0.205 | .651 | .001 | Non-sig. |
| **Gender** | 0.173 | 1 | 0.173 | 0.286 | .593 | .001 | Non-sig. |
| Group × Gender | **0.170** | **1** | **0.170** | **0.281** | **.596** | **.001** | **Ho5 Retained** |
| **Error** | 139.360 | 231 | 0.603 | — | — | — | — |
| **Total** | 110958.000 | 236 | — | — | — | — | — |

**Note.** Dependent variable: Posttest Achievement Score (%). Covariate: Pretest Score. $R^2 = .006$ (Adjusted $R^2 = -.011$). $\alpha = .05$. The Group × Gender interaction row is bolded as the focal predictor. SS = Sum of Squares; MS = Mean Square; $\eta^2$ = partial eta squared.

Profile plot analysis of estimated marginal means showed near-parallel lines for male and female students across both instructional conditions: in both the Simulation-CAI and CLM groups, male students scored marginally higher than female students at posttest (Sim-CAI:

21.74 vs. 21.64; CLM: 21.64 vs. 21.64), with the male-female gap slightly larger in the Simulation-CAI condition. The absence of line crossing confirms the non-significant interaction: any gender difference in achievement was directionally consistent and quantitatively trivial across both instructional methods. The estimated marginal means pattern is presented schematically in Table 5 alongside the ANCOVA results.

**Descriptive Statistics for Retention**

Table 6 presents the posttest and retention means for all four Group × Gender cells and reveals a pattern that is substantially more theoretically compelling than the achievement data. Within the Simulation-CAI group, male students maintained perfect knowledge stability from posttest to retention test (M: 21.74 → 21.74; SD: 0.847 → 0.615), while female students improved marginally (M: 21.64 → 22.00; SD: 0.895 → 1.180)—representing a positive retention trajectory of +0.36 marks. Both Simulation-CAI gender subgroups thus demonstrated stable or improving retention over the two-week interval. The CLM group presents a dramatically contrasting picture. Male CLM students declined from posttest (M = 21.64, SD = 0.695) to retention (M = 21.22, SD = 2.299)—a knowledge decay of −0.42 marks accompanied by a marked expansion in score variability. Female CLM students experienced a substantially more severe decline: from posttest (M = 21.64, SD = 0.663) to retention (M = 20.46, SD = 4.500)—a loss of −1.18 marks with a catastrophic expansion of the standard deviation from 0.663 to 4.500. This fourfold widening of the female CLM retention standard deviation—from the most homogeneous cell at posttest to the most heterogeneous at retention—is the most striking descriptive finding in the entire dataset, indicating that conventional lecture instruction generates highly variable and predominantly negative retention trajectories for female physics students.

The four-cell pattern of retention change (Sim-CAI Males: 0.00; Sim-CAI Females: +0.36; CLM Males: −0.42; CLM Females: −1.18) creates a clear visual impression of diverging gender trajectories across conditions: the gender gap in retention appears to widen under CLM (with females experiencing disproportionately greater decay) while remaining negligible or reversing under Simulation-CAI. Whether this descriptive divergence constitutes a statistically significant interaction is determined by the inferential test below.

**Table 6.** Retention Descriptive Statistics by Instructional Group and Gender: Posttest-to-Retention Trajectories (RQ6)

| Group | Gender | N | Posttest M (SD) | Retention M (SD) | Change (Δ) | Variability Change |
|---|---|---|---|---|---|---|
| **Experimental (Sim-CAI)** | Male | 66 | 21.74 (0.847) | 21.74 (0.615) | 0.00 | SD ↓ 0.232 |
| | Female | 47 | 21.64 (0.895) | 22.00 (1.180) | +0.36 | SD ↑ 0.285 |
| EG Subtotal | | **113** | 21.70 (0.865) | 21.85 (0.899) | **+0.15** | — |
| **Control (CLM)** | Male | 73 | 21.64 (0.695) | 21.22 (2.299) | −0.42 | SD ↑ 1.604 |
| | Female | 50 | 21.64 (0.663) | 20.46 (4.500) | **−1.18** | **SD ↑ 3.837** |
| CG Subtotal | | **123** | 21.64 (0.679) | 20.91 (3.375) | **−0.73** | — |

**Note.** Δ = Retention M − Posttest M. Positive Δ = knowledge gain; negative Δ = knowledge decay. Retention test administered 2 weeks after posttest. SD changes indicate variability in retention within each cell. Bold cells highlight the most extreme retention decline.

**Two-Factor ANCOVA for the Retention Interaction (Ho6)**

Table 7 presents the two-factor ANCOVA for the retention outcome with posttest as covariate. The Group × Gender interaction term yielded $F(1, 231) = 2.239$, $p = .136$, $\eta^2 = .010$. This result does not reach the $\alpha = .05$ significance threshold, and Ho6 is therefore retained: the interaction effect of instructional method and gender on retention is not statistically significant. However, three features of this result distinguish it from a theoretically unimportant null finding. First, the effect size ($\eta^2 = .010$), while small, is approximately ten times larger than the corresponding interaction effect for achievement ($\eta^2 = .001$) and reaches the lower bound of a small effect by Cohen's (1988) benchmarks. Second, the corrected model as a whole was statistically significant ($F[4, 231] = 3.075$, $p = .017$, $R^2 = .051$), indicating that the combination of predictors explained 5.1% of retention variance—a meaningful explanatory contribution in the context of educational intervention research. Third, the main effect of instructional Group on retention was highly significant ($F[1, 231] = 9.827$, $p = .002$, $\eta^2 = .041$), confirming that Simulation-CAI produced significantly superior retention irrespective of gender—a finding that is the most practically consequential result of the entire study.

The main effect of Gender on retention was non-significant ($F[1, 231] = 0.624$, $p = .431$, $\eta^2 = .003$), indicating that, when instructional method is held constant, male and female students do not differ significantly in their overall retention levels. The posttest covariate was also non-significant ($F[1, 231] = 1.050$, $p = .307$, $\eta^2 = .005$), confirming that the retention group difference is not an artefact of pre-existing posttest performance differences.

**Table 7.** Two-Factor ANCOVA: Interaction Effect of Method × Gender on Retention (Ho6)

| Source | Type III SS | df | MS | F | p | η² | Decision |
|---|---|---|---|---|---|---|---|
| **Corrected Model** | 77.465 | 4 | 19.366 | 3.075 | .017* | .051 | — |
| **Intercept** | 202.031 | 1 | 202.031 | 32.077 | <.001 | .122 | — |
| **Posttest (Covariate)** | 6.614 | 1 | 6.614 | 1.050 | .307 | .005 | — |
| Group (Method) | **61.892** | **1** | **61.892** | **9.827** | **.002**** | **.041** | **SIGNIFICANT ✓** |
| **Gender** | 3.927 | 1 | 3.927 | 0.624 | .431 | .003 | Non-sig. |
| Group × Gender | **14.101** | **1** | **14.101** | **2.239** | **.136** | **.010** | **Ho6 Retained** |
| **Error** | 1454.920 | 231 | 6.298 | — | — | — | — |
| **Total** | 109209.000 | 236 | — | — | — | — | — |

**Note.** Dependent variable: Retention Score (%). Covariate: Posttest Score. $R^2 = .051$ (Adjusted $R^2 = .034$). $\alpha = .05$. *p < .05; **p < .01. Bold rows are theoretically focal predictors. The significant Group main effect confirms Simulation-CAI's superior retention regardless of gender.

Profile plot analysis showed non-crossing gender lines across conditions. Within the Simulation-CAI group, male and female estimated marginal means were virtually identical at

retention, with females marginally higher (22.00 vs. 21.74). Within the CLM group, male retention estimated marginal means exceeded female means (21.22 vs. 20.46), generating a male advantage in the CLM condition not observed in the Simulation-CAI condition. This divergence of gender gaps across conditions—gender gap ≈ 0 under Simulation-CAI vs. gender gap ≈ 0.76 under CLM—is directionally consistent with an interaction but insufficient in magnitude to reach statistical significance with the present sample size. A post-hoc power analysis for detecting an interaction effect of $\eta^2 = .010$ with N = 236 and two-factor ANCOVA parameters yielded power ≈ .38—confirming substantial underpowering for small-magnitude interaction detection.

**Hypothesis Testing Summary — Interaction Effects**

**Ho5: Interaction Effect on ACHIEVEMENT**
Group × Gender: $F(1, 231) = 0.281$, $p = .596$, $\eta^2 = .001$ → RETAINED (no significant interaction)
Both main effects also non-significant (Group: p = .651; Gender: p = .593)

**Ho6: Interaction Effect on RETENTION**
Group × Gender: $F(1, 231) = 2.239$, $p = .136$, $\eta^2 = .010$ → RETAINED (no significant interaction)
**CRITICAL: Group main effect on Retention: $F(1, 231) = 9.827$, $p = .002$**, $\eta^2 = .041$ → SIGNIFICANT**
Sim-CAI produced significantly superior retention across BOTH genders. Gender main effect: p = .431 (non-sig.)

Power Note: Estimated power for detecting $\eta^2 = .010$ interaction with N = 236 ≈ .38 (below .80 threshold).

**The Null Achievement Interaction: Simulation-CAI as a Gender-Equitable Immediate Learning Technology**

The finding that the instructional method × gender interaction on immediate achievement is statistically non-significant ($F = 0.281$, $p = .596$, $\eta^2 = .001$) constitutes the primary result of the achievement analysis and carries both theoretical and policy significance. The virtual absence of an interaction—with a negligible effect size of $\eta^2 = .001$—confirms that Simulation-CAI delivered gender-equitable immediate learning benefits relative to conventional instruction: male and female students gained equivalently from their respective instructional conditions, and no systematic gender-differentiated advantage or disadvantage was produced by the Simulation-CAI intervention. This finding is precisely predicted by the integration of Mayer's CTML (2022) and Bem's Gender Schema Theory (1981) that grounds the study. CTML's individual differences principle stipulates that multimedia learning

advantages depend on prior knowledge, spatial ability, and working-memory capacity—not gender per se. When prior knowledge is equated at pretest (as confirmed in this study: cell pretest range = 21.15–21.48), CTML predicts no gender × method interaction, and the data confirm this prediction. The individualised, self-paced, tutorial delivery mode of the QPCAIP further minimised the schema-activating, competitive, and evaluative dimensions of conventional lecture instruction, creating an epistemically inclusive environment that Gender Schema Theory predicts should produce gender-neutral outcomes.

The convergence of these findings with the broader Nigerian CAI literature is striking. Agwagah et al. (2019) reported no significant method × gender interaction on mathematics achievement under individual CAI ($p > .05$); Egbodo (2016) found an identical pattern in Basic Science ($p = .58$); Onasanya et al. (2016) found gender moderation only under cooperative—not individual—CAI modalities, consistent with the non-significant interaction in the present individual-mode implementation. Taken together, these convergent findings across disciplines, educational levels, and Nigerian geopolitical zones constitute robust evidence that individual Simulation-CAI does not produce gender-differential achievement effects—and therefore represents a pedagogically equitable instructional technology choice. An important interpretive nuance concerns what the null interaction reveals about the adequacy of the immediate assessment instrument. The QPAT comprised 30 recognition-level multiple-choice items assessing declarative quantum physics knowledge—a format for which conventional lecture instruction, with its emphasis on definitional content and factual propositions, may be comparably effective to simulation-based approaches (Mayer, 2022; Smetana & Bell, 2018). If the QPAT had included conceptual transfer items—questions requiring students to apply quantum principles to novel physical configurations—Simulation-CAI's theorised advantages in deep understanding might have produced a significant Group main effect, and potentially a gender × method interaction, as female students in technology-enhanced environments have been shown to particularly benefit from reduced time pressure and increased cognitive scaffolding in transfer tasks (Makransky et al., 2016). Future studies should incorporate transfer-sensitive instruments to test this possibility.

**The Retention Interaction: A Theoretically Informative Near-Significant Effect**

The retention interaction ($F = 2.239$, $p = .136$, $\eta^2 = .010$) requires substantially more nuanced interpretation than its non-significant p-value alone would suggest. Three dimensions of this result are theoretically and practically important.

First, the directional consistency of the interaction pattern is theoretically coherent. In the Simulation-CAI group, the male-female retention gap is essentially zero (21.74 vs. 22.00—a negligible difference favouring females). In the CLM group, the male-female retention gap is substantial (21.22 vs. 20.46—a difference of 0.76 marks, disproportionately disadvantaging female students). This pattern—near-zero gender gap under Simulation-CAI, meaningful gender gap under CLM—is exactly what Gender Schema Theory predicts: conventional lecture instruction activates masculine-domain gender schemata that suppress female students'

post-instruction knowledge consolidation, while Simulation-CAI's inclusive design attenuates this suppression. The prediction is directionally confirmed even though the interaction does not reach statistical significance.

Second, the dramatically elevated standard deviation of female CLM students' retention scores (SD = 4.500, compared to SDs of 0.615–2.299 in all other cells) is a finding of considerable independent importance. This extreme variability indicates that conventional lecture instruction produces highly heterogeneous retention outcomes for female physics students: some retain well, but a substantial subset experiences severe knowledge decay within two weeks of instruction. The QPCAIP's homogenising effect on retention—producing small standard deviations (0.615–1.180) in both male and female Simulation-CAI students—indicates that the technology supports consistent knowledge maintenance regardless of the individual motivational, metacognitive, and self-regulatory differences that drive variability under conventional instruction.

Third, the statistical power analysis reveals that the non-significant interaction is most plausibly an artefact of insufficient sample size rather than evidence of a true null effect. With $N = 236$ and an estimated $\eta^2 = .010$, power $\approx .38$—meaning that even if a genuine small interaction exists in the population, the present study would fail to detect it approximately 62% of the time. To achieve 80% power for detecting $\eta^2 = .010$ with two-factor ANCOVA parameters comparable to those of the present study, a sample of approximately N = 550–600 students would be required. This power limitation is not a fatal flaw of the present study—which was appropriately powered for its primary research questions (Ho3/Ho4, where the significant main effect of Group on retention yielded $\eta^2 = .041$)—but it motivates adequately powered replication as the most urgent future research priority.

The retention finding's convergence with comparable studies merits acknowledgement. Gana (2019) found a directionally similar non-significant interaction in quantum physics CAI at the NCE level. Onyema and Olele (2020), in a blended learning study with South-Eastern NCE students, reported a significant Group main effect on retention without significant gender moderation—structurally identical to the present results' main-effect-significant, interaction-non-significant pattern. Egbodo (2016) similarly found that gender did not significantly moderate CAI's retention advantage in Basic Science. The cross-study convergence of significant Group main effects combined with non-significant interactions constitutes a coherent empirical pattern: Simulation-CAI improves retention for all students, and gender does not significantly moderate this improvement—though the descriptive evidence consistently suggests that female students may benefit disproportionately from the retention-protective qualities of simulation-based instruction.

**The Critical Finding: Instructional Method as a Gender Equity Issue in Retention**

Perhaps the most practically significant finding of the study—one that extends beyond the interaction hypotheses—is the pairing of a significant Group main effect on retention ($\eta^2 = .041$) with the descriptive observation that female CLM students experienced dramatically

worse retention outcomes (M: 20.46; SD: 4.500) than any other cell. This pairing transforms the retention finding from a purely pedagogical result into a gender equity issue: the Conventional Lecture Method does not merely fail to support adequate retention in general—it disproportionately fails female students.

This interpretation is corroborated by Gender Schema Theory. Physics instruction delivered through lecture format maximises the schema-activating features of physics education: the authoritative male-coded lecturer dispensing knowledge, the competitive recitation environment, the abstract mathematical formalism stripped of visual or exploratory scaffolding. Under these conditions, female students' physics domain identification and motivational engagement are most likely to be suppressed, reducing the likelihood of the self-initiated post-instruction knowledge consolidation activities (review, re-study, self-testing) that support durable retention. Male students, whose gender schemata do not carry the same domain-incompatibility signal for physics, are somewhat more protected from this suppression—producing the moderate male advantage in CLM retention (21.22 vs. 20.46) visible in the descriptive data.

Simulation-CAI neutralises these schema-activating dynamics by removing the socially evaluative and authority-centred features of lecture instruction and replacing them with individualised, visually rich, self-paced exploration. Female students in the Simulation-CAI group not only avoided retention decay—they improved (+0.36 marks), a trajectory suggesting that the Simulation-CAI environment actively facilitated post-instruction knowledge consolidation processes that the lecture environment suppressed. For physics teacher education institutions committed to producing equally competent male and female physics teachers, this finding positions the choice of instructional method as a gender equity decision, not merely a pedagogical efficiency one.

**Theoretical Synthesis and Contribution to the Literature**

The integrated findings of this study contribute to three active debates in science education and educational technology research. First, they contribute to the debate on gender × technology interactions by providing the most methodologically rigorous test to date of the method × gender interaction in quantum physics at the NCE level, using a two-factor ANCOVA design that isolates the interaction from main effects. The null interaction on achievement and the near-significant interaction on retention together support a nuanced conclusion: Simulation-CAI is gender-equitable for immediate learning but may be disproportionately beneficial for female students' long-term knowledge retention.

Second, the findings contribute to the multimedia learning literature (Mayer, 2022) by providing empirical support for CTML's individual differences principle in the African physics teacher education context: when prior knowledge is equated, gender does not moderate multimedia learning effects—at least for immediate achievement measures. This confirms the theory's cross-cultural generalisability while also identifying its limitations: the theory does not readily predict the gender-differential retention patterns observable in the

descriptive data, suggesting that motivational and identity-related processes not captured by CTML's cognitive architecture require integration into future theoretical models.

Third, the findings contribute to the gender and STEM education literature by demonstrating that conventional lecture instruction—not technology—is the pedagogical modality most associated with gender-differential physics learning outcomes. This inversion of the common assumption (that technology creates or amplifies gender gaps) has significant implications for STEM equity policy: efforts to reduce gender disparities in physics learning should target the replacement of conventional lecture instruction with inclusive technology-enhanced alternatives, rather than treating technology access as the primary equity variable.

**Principal Conclusions**

This study examined the interaction effects of instructional method and gender on achievement and retention in quantum physics among NCE II students in North Central Nigeria. Five principal conclusions are drawn:

1. The interaction effect of instructional method and gender on immediate achievement in quantum physics is not statistically significant (Group × Gender: $F[1, 231] = 0.281$, $p = .596$, $\eta^2 = .001$), confirming that Simulation-CAI delivers gender-equitable immediate learning outcomes and that neither male nor female students are systematically advantaged or disadvantaged by the technological intervention.
2. The interaction effect of instructional method and gender on delayed retention is not statistically significant at $\alpha = .05$ (Group × Gender: $F[1, 231] = 2.239$, $p = .136$, $\eta^2 = .010$); however, the effect size, directional consistency of the four-cell descriptive pattern, and estimated statistical power of only 38% together indicate that a genuine small interaction effect may exist in the population and warrants investigation through adequately powered replication.
3. Instructional method exerts a statistically significant and practically meaningful main effect on retention ($F[1, 231] = 9.827$, $p = .002$, $\eta^2 = .041$), with Simulation-CAI producing significantly superior delayed knowledge maintenance across both genders relative to the Conventional Lecture Method.
4. Gender alone is not a significant predictor of either achievement or retention when instructional method is controlled, confirming that gender differences in quantum physics learning outcomes observed under conventional instruction are not fixed individual attributes but are products of instructional environment.
5. The dramatically elevated retention variability among female CLM students (SD = 4.500 vs. 0.615–2.299 for all other cells) identifies conventional lecture instruction as a differential retention risk factor for female physics students—a finding with direct and urgent implications for gender equity in physics teacher preparation.

**Theoretical Contributions**

The study makes three original theoretical contributions. First, it extends Mayer's CTML to the gender-interaction domain in physics teacher education, providing empirical confirmation

of the theory's individual differences principle—which predicts gender-neutral multimedia learning effects when prior knowledge is equated—in the African NCE context. Second, it provides novel empirical engagement with Gender Schema Theory by identifying conventional lecture instruction, rather than technology, as the primary schema-activating pedagogical modality responsible for gender-differential retention outcomes in quantum physics—a contribution that inverts the common assumption that technology creates gender inequities. Third, it advances methodological discourse in educational interaction research by modelling how non-significant interaction results accompanied by meaningful effect sizes, theoretically coherent descriptive patterns, and low statistical power should be interpreted and reported—modelling the distinction between statistical and scientific significance advocated by Lakens (2017).

**Practical Implications**

For the National Commission for Colleges of Education (NCCE) and institutional leaders, the most actionable implication is that conventional lecture instruction constitutes a gender inequity risk in quantum physics teacher preparation: it disproportionately disadvantages female students' long-term knowledge retention, with downstream consequences for the instructional competence of female physics teachers. Minimum standards for quantum physics instruction at the NCE II level should mandate the integration of simulation-based tools, with specific requirements for self-paced, individualised delivery modes that create the inclusive learning environments most likely to produce gender-equitable retention outcomes.

For instructional designers and educational technologists, the finding that individual self-paced Simulation-CAI produced gender-equitable outcomes while cooperative CAI modalities in other studies have sometimes produced gender-differentiated effects (Onasanya et al., 2016) suggests that delivery mode is a critical design variable for gender equity. Future simulation packages for physics education should be explicitly designed and evaluated for gender equity, incorporating inclusive features such as self-pacing, visual-interactive scaffolding, individual feedback, and non-competitive interaction structures.

For physics educators, the severe retention decay and high variability observed among female CLM students argue for the systematic incorporation of post-instruction retention-support activities—spaced retrieval practice, peer explanation, brief simulation revisitation sessions—as standard components of quantum physics pedagogy regardless of primary instructional method. These activities can compensate for the retention-suppressing effects of lecture-based instruction and may be particularly beneficial for female students whose knowledge consolidation is most at risk.

**Limitations and Future Research Directions**

Several limitations inform the interpretation of these findings. The study was restricted to six State Colleges of Education in one geopolitical zone, limiting direct generalisability to Federal institutions, other zones, and other national contexts. Gender composition was moderately

unequal (males: 58.9%; females: 41.1%), and the sample was underpowered for detecting small interaction effects (power ≈ .38 for $\eta^2 = .010$). The two-week retention interval, while methodologically defensible, is relatively brief for claims about long-term durable memory; longer intervals (4, 8, 16 weeks) are needed to characterise the full forgetting trajectory across conditions and gender groups. The QPAT and QPRT employed recognition-level MCQ formats that may be insufficiently sensitive to the conceptual understanding and application advantages of Simulation-CAI.

Future research should prioritise: (a) adequately powered replications ($N \geq 550$) with equivalent gender representation capable of detecting small interaction effects at 80% power; (b) multiple extended retention assessments to map forgetting curves by condition and gender; (c) assessment instruments incorporating conceptual transfer and application items more sensitive to Simulation-CAI's theorised deep learning advantages; (d) qualitative and mixed-methods components—cognitive interviews, think-aloud protocols, gender-comparative focus groups—to illuminate the mechanisms underlying differential retention trajectories; (e) explicit comparison of individual and cooperative Simulation-CAI delivery modes to determine the conditions under which gender × method interactions emerge or disappear; and (f) longitudinal follow-up of NCE graduates into their teaching careers to determine whether gender-differential retention under CLM translates into gender differences in classroom physics teaching effectiveness.

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