Asian Journal of Education and Training
Vol. 12, No. 3, 47-54, 2026
ISSN(E) 2519-5387
DOI: 10.20448/edu.v12i3.9134

Understanding mathematical barriers to learning quantum mechanics and relativity: A qualitative study of Nigerian university students

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Abstract

This qualitative study examined the mathematical barriers Nigerian undergraduate physics students encounter in learning quantum mechanics and relativity. It explored cognitive, pedagogical, and resource-related factors influencing students' understanding of mathematically demanding concepts such as Hilbert spaces, linear operators, probabilistic formalism, Lorentz transformations, tensor calculus, and space-time curvature. Data were collected through semi-structured interviews and focus group discussions with 50 second- and third-year physics students from two Nigerian universities. Thematic analysis revealed persistent difficulties in understanding wave-particle duality, quantum superposition, the uncertainty principle, time dilation, and space-time curvature because these concepts conflict with classical intuition and rely on unfamiliar mathematical structures. Participants also identified lecture-dominated instruction, limited derivational engagement, overcrowded classrooms, and inadequate feedback as factors encouraging rote memorization rather than conceptual understanding. Inadequate access to interactive simulations, visual representations, modern textbooks, reliable internet, and laboratory facilities further hindered the development of mathematical intuition and coherent mental models. The findings indicate that learning challenges are shaped by both cognitive complexity and institutional constraints. The study recommends student-centred teaching, guided mathematical modelling, computational tools, interactive visualizations, smaller tutorial groups, and improved digital resources to strengthen mathematical reasoning, reduce misconceptions, and enhance modern physics learning in Nigerian universities and similar low-resource contexts.

Keywords: Cognitive barriers, Conceptual understanding, Physics education, Quantum physics, Relativity concepts, Students' comprehension.

Citation | Babalola, F. E., & Aladejana, A. L. (2026). Understanding mathematical barriers to learning quantum mechanics and relativity: A qualitative study of Nigerian university students. *Asian Journal of Education and Training, 12*(3), 47–54. 10.20448/edu.v12i3.9134

History:
Received: 11 June 2026
Revised: 30 July 2026
Accepted: 6 August 2026
Published: 12 August 2026

Publisher: Asian Online Journal Publishing Group

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Institutional Review Board Statement: Ethical approval for this study was obtained from the Research and Innovation Ethics Committee (RIEC) of the Federal University of Oye Ekiti, Nigeria, before data collection. The RIEC approval was granted on 20th March, 2026, with RIEC number RIEC/FUOYE/SED/RES/035. The study was conducted in accordance with accepted ethical standards for research involving human participants. All participants were informed about the purpose of the study, their right to withdraw at any stage, and the measures taken to protect confidentiality and anonymity. Written informed consent was obtained from all participants before their involvement in the study.

Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Competing Interests: The authors declare that they have no competing interests.

Authors' Contributions: Both authors contributed equally to the conception and design of the study. Both authors have read and agreed to the published version of the manuscript.

Disclosure of AI Use: The authors acknowledge the use of artificial intelligence-assisted tools for language editing, grammar correction, formatting support, and improvement of manuscript clarity. The AI tool was not used to generate data, analyze data independently, or replace the authors' scholarly judgment. All AI-assisted outputs were reviewed, verified, and edited by the authors, who take full responsibility for the accuracy, integrity, and originality of the final manuscript.

Contents

Contribution of this paper to the literature

This study provides context-specific qualitative evidence on how cognitive, pedagogical, and institutional factors jointly create mathematical barriers to learning quantum mechanics and relativity among Nigerian undergraduate physics students. It offers an integrated framework linking advanced mathematical reasoning, instructional practices, and resource limitations to inform context-sensitive reforms in modern physics education.

1. Introduction

Physics education plays a central role in preparing students for scientific, technological, and industrial development. As a foundational discipline, physics supports innovation in engineering, electronics, medical imaging, telecommunications, renewable energy, and emerging digital technologies. Within physics, quantum mechanics and relativity are especially important because they provide the theoretical basis for many modern scientific and technological advances, including quantum technologies, semiconductor devices, lasers, satellite communication, and gravitational research (Bitzenbauer, 2021; Bondani et al., 2022; Henriksen et al., 2014).

Despite their importance, quantum mechanics and relativity are widely regarded as difficult areas for undergraduate students. Their concepts often conflict with learners' everyday experiences of the physical world. Students who are familiar with classical ideas of motion, force, space, and time may find it difficult to understand concepts such as wave-particle duality, quantum superposition, uncertainty, time dilation, and space-time curvature (Bouchée, de Putter-Smits, Thurlings, & Pepin, 2022; Stadermann & Goedhart, 2020; Ubben, Veith, Merzel, & Bitzenbauer, 2023). These difficulties are often intensified by the abstract mathematical representations used in teaching these topics. As a result, many students rely on memorization of equations rather than developing meaningful conceptual understanding (Mayer, 2019; Singh & Marshman, 2015).

In Nigerian universities, these learning difficulties are further shaped by contextual factors such as weak mathematical preparation, large class sizes, limited access to modern instructional resources, and lecture-dominated teaching methods (Ogunleye & Akinsola, 2021; Okeke & Eze, 2024). Many physics classrooms still depend heavily on verbal explanations and mathematical derivations, with limited use of simulations, visualizations, laboratory demonstrations, or interactive learning strategies. Such conditions may restrict students' opportunities to connect mathematical symbols with physical meanings and may contribute to persistent misconceptions (Bondani et al., 2022; Mayer, 2019).

Although studies on students' difficulties in quantum mechanics and relativity exist, much of the literature has focused on contexts with relatively better instructional resources (Bitzenbauer, 2021; Bouchée et al., 2022). Less attention has been given to how Nigerian undergraduate students experience these abstract topics within resource-limited university environments. Understanding their challenges is important for designing context-sensitive instructional strategies that can improve conceptual learning and mathematical reasoning in advanced physics courses.

This study therefore investigates the mathematical, cognitive, pedagogical, and resource-related barriers that Nigerian undergraduate physics students encounter in learning quantum mechanics and relativity. Specifically, it explores students' difficulties with key concepts, their interpretation of abstract mathematical representations, the influence of teaching methods and learning resources, and possible strategies for improving instruction. The findings are expected to contribute to physics education research and support evidence-based reforms for teaching modern physics in Nigerian universities and similar developing contexts.

1.1. Research Questions

1. What cognitive and mathematical challenges do students face with key concepts in quantum mechanics and relativity?
2. How do students describe their understanding of abstract concepts in quantum mechanics and relativity?
3. How do teaching methods and learning resources support or hinder students' understanding of these concepts?
4. What misconceptions do students hold about quantum mechanics and relativity?
5. How can strategies be adapted to strengthen mathematical reasoning in resource-limited settings?

2. Literature Review

Learning quantum mechanics and relativity remains one of the most persistent challenges in physics education because both fields require students to move beyond everyday, classical interpretations of physical reality. Unlike many topics in introductory mechanics, modern physics concepts are not easily supported by direct sensory experience. Ideas such as quantum superposition, wave-particle duality, uncertainty, time dilation, and space-time curvature require learners to coordinate abstract concepts, mathematical representations, and unfamiliar physical interpretations (Bouchée et al., 2022; Henriksen et al., 2014; Stadermann & Goedhart, 2020). This creates a learning situation in which difficulty does not arise from content complexity alone, but from the interaction between cognition, mathematical readiness, pedagogy, and access to instructional resources.

Cognitive Load Theory provides a useful explanation for why students often struggle with these topics. Quantum mechanics and relativity impose high intrinsic cognitive load because learners must process unfamiliar concepts and symbolic representations simultaneously (Sweller, Ayres, & Kalyuga, 2019). For example, students are expected to interpret equations not only as mathematical procedures but also as representations of physical systems that often contradict everyday intuition. When instruction relies heavily on lengthy derivations, dense notation, and verbal explanation without adequate scaffolding, extraneous cognitive load may increase. This can reduce students' ability to construct meaningful conceptual schemas (Mayer, 2019). From this perspective, students' difficulties are not simply evidence of weak ability; they may reflect instructional conditions that overload working memory and limit conceptual integration.

Constructivist perspectives further clarify the problem by emphasizing that learners interpret new knowledge through existing mental structures (Piaget, 1970; Vygotsky, 1978). Students entering quantum mechanics and relativity courses often possess classical assumptions about particles, waves, space, time, causality, and certainty. These assumptions may be useful in earlier physics courses but become problematic when students encounter probabilistic, observer-dependent, and geometric interpretations of physical phenomena (Bouchée et al., 2022; Ubben et al., 2023). Previous studies have shown that students frequently retain classical mental models even after formal instruction (Singh & Marshman, 2015; Stadermann & Goedhart, 2020). This suggests that learning modern physics requires conceptual change rather than simple accumulation of new information. However, conceptual change is unlikely to occur when teaching emphasizes formula manipulation without explicitly addressing misconceptions and alternative conceptions.

Dual Coding Theory and Mental Model Theory also contribute to understanding the learning challenge. Abstract physics concepts are easier to understand when learners can connect verbal, mathematical, and visual representations (Johnson-Laird, 1983; Mayer, 2019). In quantum mechanics and relativity, however, visual representation is difficult because many phenomena cannot be directly observed or represented through familiar physical images. Probability densities, wave functions, curved space-time, and relativistic frames of reference require carefully designed visual supports. When these supports are absent, students may rely on misleading analogies or memorize equations without developing stable mental models (Stadermann & Goedhart, 2020; Ubben et al., 2023). Thus, visualization is not merely an instructional aid; it is central to meaning-making in abstract physics learning.

Empirical studies on quantum physics education have consistently reported students' difficulties with probabilistic reasoning, superposition, measurement, and wave-particle duality (Bitzenbauer, 2021; Bouchée et al., 2022; Singh & Marshman, 2015). Similar studies in relativity education show persistent misconceptions about simultaneity, time dilation, reference frames, and the nature of gravity (Gousopoulos, Kapotis, & Kalkanis, 2023; Henriksen et al., 2014). These findings indicate that students' difficulties are not isolated or incidental but represent recurring patterns across educational contexts. Nevertheless, much of the existing literature documents the presence of misconceptions without sufficiently examining how such misconceptions are shaped by local instructional conditions. This limits the explanatory value of the literature for developing countries where structural constraints may intensify already complex learning demands.

Studies on instructional interventions suggest that active learning, simulations, visualizations, peer discussion, and inquiry-based activities can improve students' understanding of abstract physics concepts (Bondani et al., 2022; Mayer, 2019; Ubben et al., 2023). These approaches are valuable because they create opportunities for students to test assumptions, compare representations, and link mathematical formalism with physical meaning. However, the effectiveness of such interventions depends on institutional capacity. In contexts where class sizes are large, laboratory facilities are limited, internet access is unreliable, and lecturers are pressured to complete dense syllabi, the adoption of interactive pedagogies may be difficult (Ogunleye & Akinsola, 2021; Okeke & Eze, 2024). Therefore, the question is not only whether student-centred methods work, but how they can be adapted to resource-limited university environments.

In Nigerian universities, the challenges associated with learning quantum mechanics and relativity are compounded by broader educational and infrastructural factors. Students may enter university with uneven mathematical preparation, limited exposure to modern physics at the secondary level, and little experience with abstract modelling (Ogunleye & Akinsola, 2021; Okeke & Eze, 2024). At the same time, many physics departments face overcrowded classrooms, inadequate laboratory facilities, limited access to digital tools, and dependence on lecture-based instruction. These conditions may encourage procedural learning, where students focus on passing examinations through memorized derivations rather than developing conceptual understanding. Consequently, mathematical abstraction becomes both a cognitive challenge and a structural educational problem.

The literature therefore shows broad agreement that quantum mechanics and relativity are difficult to learn because they demand advanced abstraction, conceptual change, and representational fluency (Bitzenbauer, 2021; Bouchée et al., 2022; Stadermann & Goedhart, 2020). However, a major gap remains in understanding how these difficulties are experienced by undergraduate physics students in Nigerian universities. Existing studies have paid limited attention to the combined influence of mathematical barriers, teaching practices, and resource constraints in shaping students' comprehension of modern physics. This study addresses that gap by examining Nigerian students' lived experiences of learning quantum mechanics and relativity, with particular attention to how cognitive, pedagogical, and institutional factors interact. By doing so, it contributes to a more context-sensitive understanding of abstract physics learning in resource-limited higher education settings.

3. Method

3.1. Research Design

This study adopted a qualitative exploratory research design to investigate the mathematical, cognitive, pedagogical, and resource-related barriers that undergraduate physics students encounter in learning quantum mechanics and relativity. The design was appropriate because the study sought to understand students' lived experiences, perceptions, and interpretations of abstract physics concepts within their institutional learning contexts (Bitzenbauer, 2021; Creswell & Poth, 2018; Krijtenburg-Lewerissa, Pol, Brinkman, & van Joolingen, 2021).

3.2. Participants and Sampling

The participants comprised 50 undergraduate physics students drawn from two public universities in Southwest Nigeria. For ethical and institutional confidentiality reasons, the universities are identified as University A and University B. The institutions were selected to reflect variation in institutional setting, resource availability, teaching conditions, and learning environment. Participants were second- and third-year students enrolled in physics-related undergraduate programmes who had either completed or were currently taking courses in quantum mechanics and/or relativity. A purposive sampling technique was used because the study required participants with direct academic exposure to the concepts under investigation. First-year students were excluded because of their limited exposure to advanced physics topics.

3.3. Data Collection

Data were collected through semi-structured interviews and focus group discussions. Twenty-five students participated in individual interviews, while the remaining 25 participated in four focus group discussions. The interviews allowed participants to provide detailed personal accounts of their learning difficulties, while the focus groups generated shared perspectives on classroom experiences, teaching methods, mathematical challenges, and resource limitations. The questions focused on students' understanding of key concepts such as wave-particle duality, quantum superposition, uncertainty principle, time dilation, and space-time curvature. All sessions were conducted with participants' consent, audio-recorded, and transcribed for analysis.

3.4. Data Analysis, Trustworthiness, and Ethics

Data were analyzed using reflexive thematic analysis following (Braun & Clarke, 2019). The analysis involved familiarization with the data, generation of initial codes, identification of themes, review and refinement of themes, naming of themes, and production of the final report. NVivo software was used to support data organization and coding. Trustworthiness was strengthened through methodological triangulation, member checking, peer debriefing, thick description, and maintenance of an audit trail. Credibility was enhanced by comparing evidence from interviews and focus groups, while dependability and confirmability were supported through transparent documentation of coding decisions and analytic interpretations.

Ethical approval was obtained from the relevant institutional ethics committees before data collection. Participants were given information sheets and provided signed informed consent. They were informed of their right to withdraw from the study at any point without penalty. Confidentiality was maintained through the use of participant codes and institutional anonymization. All data were securely

4. Results

The qualitative data from twenty-five semi-structured interviews and four focus group discussions with fifty second- and third-year undergraduate physics students in two Nigerian Universities (one in the North and one in the South) were thematically analysed to identify three broad and interconnected themes: cognitive, pedagogical and resource-related challenges. The mentioned themes encapsulate the main difficulties that learners face while trying to understand fundamental abstract concepts in quantum mechanics (wave-particle duality, quantum superposition, uncertainty principle) and in relativity (time dilation, length contraction, space-time curvature).

Each theme includes representative quotations from participants and estimates of approximate frequency based on coding prevalence across transcripts.

4.1. Cognitive Obstacles

The issue of cognitive challenges was the most talked-about. Participants shared that the highly counterintuitive nature of the topic was the greatest challenge they faced. People's regular physical experiences are macroscopic and deterministic. So, when they see quantum phenomena, they don't expect gobbledygook; they expect some gobbledygook.

Table 1. Cognitive Challenges in Understanding Quantum Physics and Relativity.

Challenge	Description	Frequency of Mention
Wave-particle duality	Difficulty in conceptualizing particles behaving as both waves and particles.	70%
Quantum superposition	Trouble understanding that particles can exist in multiple states simultaneously.	65%
Time dilation	Difficulty visualizing how time slows down at high velocities.	60%
Space-time curvature	Struggling to grasp the bending of space-time under the influence of mass and energy.	75%
Uncertainty principle	Confusion around the idea that certain pairs of physical properties cannot be precisely known.	55%

Table 1 presents the major cognitive challenges experienced by undergraduate physics students in understanding quantum mechanics and relativity, together with the frequency with which each challenge is mentioned by participants.

In quantum physics, wave-particle duality and superposition triggered the most intense expressions of confusion. Many students have difficulty with classical categories for objects as either particle or wave and almost cannot comprehend a system existing in more than one state at once.

I don't understand quantum physics; the particles act in ways that I can't even imagine. In what ways can things act as both particles and waves? It's as if it's not following the rules of reality. (Participant 5, Interview).

"*Superposition is very bad. As the saying goes, until you look, the particle is in many places, but in real life things are either here or there. My brain won't allow it. It's just too weird. Too impossible.*" (P17, FG2)

Probabilistic reasoning and the uncertainty principle elicit similar reactions. Many participants thought it frustrating because nothing can be known with certainty.

Relativity had similar problems. Participants' long-held intuition that time is universal and space is flat and static was directly contradicted by ideas like time dilation and space-time curvature. Representing these effects proved especially problematic.

I find it rather strange that time can be different depending on how quickly one is moving. How can time differ? I can't see how that works in real life. Time is time, it's the same for everyone. (P12, FG1).

Is space curved around a massive object? Like how gravity bends space? This could be from sci-fi. I attempt to visualize it, yet my mind goes blank there's nothing from every day that compares. (Participant 9, Interview).

Throughout the transcripts, the students often reported being unable to picture anything stable in their minds about those phenomena. This pattern of mental confusion with no stable image often resulted in emotional confusion. The students also often reported getting stuck on rote formulas rather than having proper concepts. Most interviews and focus groups referenced these difficulties.

4.2. Pedagogical Problems

The second main theme dealt with limitations of current teaching practices. According to the respondents, classroom teaching takes place mainly through lectures, where teachers deliver content verbally, write on the blackboard, and make presentations on slides without much scope for engagement or discussion of concepts.

Table 2. Pedagogical Issues in Teaching Quantum Physics and Relativity.

Pedagogical Issues	Description	Frequency of Mention
Lecture-based teaching	Predominance of lecture methods without hands-on activities or interactive components.	80%
Lack of practical examples	Absence of real-world applications or demonstrations to help students relate theory to practice.	65%
Large class sizes	Difficulty in providing personalized feedback and support in large lecture environments.	70%
Limited use of interactive learning	Insufficient integration of digital tools, simulations, and group discussions.	75%
Inadequate feedback	Lack of individualized feedback, leaving students uncertain about their understanding.	60%

Table 2 presents the major pedagogical issues identified by participants in the teaching of quantum physics and relativity, together with the frequency with which each issue is mentioned during the interviews and focus group discussions.

Lecturers often discuss these types of things in class, but we don't really understand. It was all theory and no practical examples or experiments, just chalk and talk from morning till end. (Participant 8, Interview).

Considered unsuitable for abstract counter-intuitive subject matters, this transmissive style was quite popular. Students like to have interactive methods to a bigger extent.

If we did some group discussions or could play with simulations, maybe superposition would click. However by the time 200 who are attending classes, the lecturer will just skim through slides with no time for questions or real talk. (Participant 4, Focus Group 3).

Being in a class of 150–200 students limits the opportunity for individual attention and feedback.

In a lecture of more than 200 students, you cannot receive feedback. We strictly learn the formulas and pass the exam but don't understand the concepts really. Until the final no one knows if we're getting it wrong. (Participant 4, Focus Group 1)

Participants observed that not getting any timely, constructive feedback made them feel uncertain about their understanding and strengthened surface learning strategies. Active learning methods (group problem-solving, peer discussion, inquiry tasks) were reported to be infrequent or nonexistent, largely due to the pressure of time, overcrowding, and institutional norms valuing content coverage over conceptual coverage.

4.3. Obstacles Related to Resources

The other major theme involved the lack of learning resources that can help visualise and explore abstract phenomena. Participants highlighted that the unavailability of visual aids, interactive simulations, animations and modern laboratory apparatus thwarted their ability to develop correct mental models.

Table 3. Resource-Related Barriers in Learning Quantum Physics and Relativity.

Resource Barrier	Description	Frequency of Mention
Lack of visual aids	Absence of simulations, videos, or animations to help visualize abstract concepts.	85%
Limited access to technology	Few resources for interactive learning, such as software or virtual labs.	78%
Outdated textbooks	Textbooks that are difficult to understand and lack modern examples or explanations.	70%
Inadequate online resources	Limited availability of up-to-date online content on quantum physics and relativity.	68%
Insufficient laboratory equipment	Lack of advanced laboratory setups for practical experiments related to quantum physics.	72%

Table 3 presents the major resource-related barriers encountered by undergraduate physics students in learning quantum physics and relativity, together with the frequency with which each barrier is mentioned by participants.

We lack adequate resources. Instructional videos or animations explaining how things work at the quantum level, or how time "bends" around massive objects, would make it easier to understand. Currently, it is no more than just a series of words and equations on the board.

Among group discussions and interviews held at various stages (see Data Collection), many students made it clear that a need for dynamic visualisations was present. In nearly all group discussion sessions, students argued that static diagrams and textbook representations were not sufficient to grasp diametric and non-intuitive processes.

Textbooks were often considered outdated, poorly illustrated or not clearly explaining key ideas.

My textbooks are obviously aged (some are from the 1990s!) and they are not clear and they don't explain things well." Space-time diagrams don't exist, nor do examples for entanglement. Participant 14 in Focus Group 4 stated, *"We can't even search anything of quality online because the Wi-Fi is always down or too slow."*

Most of the participants had little or no access to computers, simulation software, virtual labs or reliable internet. The lack of actual or virtual experimental opportunities was often associated with one's inability to 'see' or 'feel' the phenomenon in question

If we could run simulations on computers, we'd be able to see wave functions collapsing and clocks ticking slower in rockets. We lack the things necessary to bring our theory to life.

Perceived resource constraints were thought to exacerbate cognitive difficulties and the limitations of lectureware, resulting in growth in superficial engagement and conceptual misunderstanding.

5. Discussion

The study, which is qualitative in nature, found a number of barriers to Nigerian university students' understanding of abstraction in quantum mechanics and relativity. Conceptual change problems, dependence on transmissive teaching practices, and a lack of enabling tools and an appropriate environment have created serious conditions in the education system. Prior research in the field of physics education, both in international and developing-country contexts, shows substantial agreement in the results. It also shows how the problems are exacerbated and perpetuated by systemic constraints in Nigerian higher education.

5.1. Cognitive Challenges and Conceptual Change

Respondents revealed that they faced severe challenges with things that are counterintuitive: wave-particle duality, quantum superposition, uncertainty principle, time dilation and curvature of space-time. Students' mental models are classical and deterministic (shaped by everyday macroscopic experiences), while modern physics being probabilistic, non-local, relational, and relativistic (Bouchée et al., 2022; Tsai, 2020), gives rise to the difficulties. The feelings of frustration of the respondents and their reference to limits of visualization as well as return to classical analogy show a common tendency where learners impose realist interpretation onto quantum and relativity (Krijtenburg-Lewerissa et al., 2021; Ubben et al., 2023).

The cognitive hurdles align with extensive evidence that the abstract character of physics demands not only mathematical competency but also radical re-conceptualisation (Foley & Tönsing, 2020). Shifting from absolute ontologies to relative or probabilistic ontologies is very difficult for students as it entails giving up strong beliefs about causality, locality and determinism (Alstein, Krijtenburg-Lewerissa, & Goedhart, 2021). In Nigeria, early exposure during secondary school to modern physics concepts dominated by classical mechanics worsens the situation. Thus, the undergraduates that are not adequately prepared for the paradigm shift did in turn not prepare adequately (Afolabi & Alabi, 2020; Obi, Ogujor, & Omokaro, 2019). Countries across the globe encounter this issue as students at all levels of education continue to hold onto these classical misconceptions, and thus reject the non-intuitive ideas of superposition and time dilation (Anttila, Lehtinen, & Koskinen, 2024; Stadermann & Goedhart, 2020). The present results thus affirm the belief that sensible mastery requires scaffolding that promotes ontological and epistemological reconfiguration, and that processes of conceptual change are not automatic or simple (Mayer, 2019; Piaget, 1970).

5.2. Pedagogical Issues

Lecture-style instructional practices, which lacked interaction and overcrowded classrooms with minimal formative feedback, were identified as a major barrier to meaningful conceptual engagement (Eze, Nwosu, & Okafor, 2021; Obi et al., 2019). Students reported feeling disconnected from the material due to large class sizes not permitting personal attention and exchange and would memorize it parrot fashion instead of integrating the material.

We cannot learn abstract topics through traditional expository methods. According to Wang, Tan, and Zhang (2020) strong evidence supports the idea that it does not help students to generate new mental representations needed for conceptual change. To the contrary, the use of student-centered strategies, including group discussions, inquiry-based tasks, and working directly with ideas, is more beneficial in scaffolding understanding by encountering and resolving misconceptions through more active learning (Bondani et al., 2022; Nautiyal et al., 2025). This situation is not addressed too often because of the institutional pressure to cover rather than engage with such materials. Nigerian tertiary institutions have been accused of the same. Students do not receive adequate pay, transfer, promotion, and training, while classroom settings do not allow the teacher-staff an opportunity to pay attention, give feedback in a timely manner, and manage the classroom (Ahmad et al., 2023; Fadipe, 2025; Okeke & Eze, 2024). According to Confusion and Dispositional Attributes of Learning an analysis can then help in effecting simple changes.

5.3. Resource Related Barriers

Participants reported repeated problems with visualization and internalization as a result of: lack of visual aids, simulation and practical kits, relevant books, reliable internet access and laboratory facilities (Afolabi & Alabi, 2020). Heavy reliance on static (and verbal-symbolic) descriptions of phenomena such as wave function collapse, relativistic effects, or a superposition state because of the absence of sales dynamic representations (e.g., animations) restricts dual coding (and model building), which helps in the understanding of non-intuitive phenomena (Mayer, 2019; Stadermann & Goedhart, 2020).

Resource shortages of this nature are well established in physics education in developing countries, with weak technical facilities limiting practical and multimedia-based learning (Fox, Zwickl, & Lewandowski, 2020; Majidy, 2024). Numerous evidence exists to prove that teachers not having technological tools and visual materials to engage students with counterintuitive ideas makes them depend on rote strategies (Ogunleye & Akinsola, 2021). In the country's universities, access to basic online simulations or virtual laboratories is hampered by chronic underfunding, outdated equipment, and poor infrastructure (like intermittent electricity and internet), which further exacerbate these problems (Akinwumi, Adeyemi, & Ojo, 2025; Okoro, Eze, & Nwankwo, 2025). The strong support of the participants for interactive tools is indicative of their belief in the potential of these tools to improve the intuition-theory gap. Research indicates that learning physics content may benefit from the use of multimedia environments by improving accessibility, clarity of concepts, and motivation (Bondani et al., 2022; Goorney, Fuentes, & Mills, 2025).

5.4. Implications and Recommendations

The connection between these three ideas, in which high intrinsic cognitive demands are compounded by poor teaching methods and a low level of resources, has significant consequences for the reform of physics education in Nigerian universities and other low-resource contexts. Essentially, it is necessary to consciously transition from lecturing to more active and student-centred methods (Anttila et al., 2024; Wang et al., 2020).

A major capital investment is of high strategic importance. Institutions should prioritize affordable digital tools (open-source quantum and relativity simulators), up-to-date textbooks, and reliable constant availability of high-quality infrastructure for viewing as well as interaction (Goorney et al., 2025; Majidy, 2024). Faculty development programs that emphasize contemporary teaching pedagogies, technology integration and conceptual teaching at the same time would effectively orient teachers to implement the change. Computer models, virtual laboratories and peer dialogues could provide necessary scaffolding for conceptual change. By using simulations and virtual experiments, students can experience more abstract physical phenomena in easier ways (Bondani et al., 2022; Nautiyal et al., 2025).

Furthermore, the application of targeted policies that assist in easing large class sizes, such as lecturer-student ratios, tutorial sub-groups or blended learning, may allow for a more person-centred instruction and formative feedback (Eze et al., 2021; Obi et al., 2019). These components are essential for identifying and addressing misconceptions early on, preventing frustration and allowing students to remain engaged with learning situations.

Structural interventions such as redesigning the curriculum to introduce modern physics early, sustained funding of STEM and partnerships to share resources may help address foundational deficits (Akinwumi et al., 2025; Okeke & Eze, 2024). Thus, if Nigerian institutions align or get their practices and activities to follow evidence-based principles, then they can improve equity in physics, empower students for quantum-related technologies and promote scientific literacy, especially in developing contexts.

Findings from this research can enrich the global discourse on abstract education in physics. Almost everyone faces cognitive barriers (Bouchée et al., 2022; Krijtenburg-Lewerissa et al., 2021), which are made worse in low-resource contexts. The answer requires local engagement and multifaceted solutions. Going forward, researchers need to evaluate particular intervention models to establish an evidence base for scalable and sustainable solutions.

6. Conclusion

According to this qualitative study, the factors that Nigerian undergraduate physics students encounter in comprehending abstract ideas in quantum mechanics and relativity are combined, persistent, and interacting in nature. Consequently, there is often widespread visualization difficulty or conceptual confusion. The cognitive challenges are made worse by limited previous exposure to modern physics ideas, and the difficulty for people to change concepts about abstract topics is generally very high. Moreover, if these abstract topics are taught in resource-poor settings, then this problem is made even worse.

From an educational perspective, large classes and lecture-type teaching were the norm; they were characterized by mostly non-interactive environments, little formative feedback, and few opportunities for active participation. Resource-related barriers exacerbated these challenges. Learning outcomes were hampered by barely any student access to interactive simulations, visual images, up-to-date textbooks, functional digital access, and working laboratories. Participants often reported that dynamic visualizations and hands-on exploration would greatly help. Evidence-based knowledge confirms that multimedia and technology-mediated environments help bridge intuition-theory gaps in physics, which usually has an abstract worldview.

To overcome these obstacles, there is a need for intentional and multi-layered reforms in Nigerian universities. Greater personalized learning, such as estimates of a similar size used, and greater use of teacher-researched pedagogy would be more appropriate for the support of concept change. Similar to the above, investment in digital materials & resources, updated material development, and multi-faculty training is important. This evidence-informed change effort can promote understanding and student engagement with physics, as well as enhance the scientific capacity of developing contexts. The educational institutions will help contribute to equality and preparedness for quantum technologies.

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