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Empirical Paper

AI-Assisted Multilingual Pedagogy in Computing Education: A Culturo-Techno-Contextual Approach Framework for Enhancing Achievement and Attitudinal Outcomes in Mobile and Adaptive Systems

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Abstract

Purpose: This study evaluated the effects of the traditional lecture method and three CTCA 2.0-based modalities (Monolingual AI-supported CTCA, Strategic Multilingual AI-supported CTCA, and Heavy Multilingual AI-supported CTCA) on students' academic performance and attitudes toward learning the OSI model.

Methodology: A quasi-experimental design involving four intact groups ($N = 75$) was adopted. Pre-test and post-test data were analysed using MANCOVA, with pre-test scores serving as covariates.

Results: Findings revealed a significant overall difference among the instructional approaches (Wilks' $\Lambda = .129$, $p < .001$). Although the CTCA 2.0 groups recorded higher achievement means than the control group, this difference in post-test achievement was not statistically significant, $F(3, 69) = 2.49$, $p = .07$. However, instructional approach exerted a very large and significant effect on students' attitudes, $F(3, 69) = 130.87$, $p < .001$, $\eta^2 = .851$, with all CTCA modalities yielding positive outcomes.

Novelty and Contributions: This study advances computing education by integrating AI-supported multilingual CTCA 2.0 strategies for teaching abstract computing concepts, and by demonstrating their strong influence on learners' affective engagement.

Practical and Social Implications: The findings suggest that culturally responsive, technology-enhanced instructional approaches can improve learners' attitudes toward challenging computing topics, thereby fostering engagement, inclusion, and sustained learning.

Keywords: Multilingual Instruction; OSI Model; Student Attitude; Academic Achievement; Mobile and Adaptive Systems.

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1 Introduction

The Open Systems Interconnection (OSI) model is a foundational conceptual framework in computer networking education. Despite its importance, students frequently demonstrate poor performance and negative attitudes toward learning the OSI model. Research consistently identifies the OSI model as an abstract, cognitively demanding topic that challenges learners' conceptual understanding and engagement. This literature review synthesises current research on student difficulties, performance issues, and attitudes toward the OSI model, drawing on recent empirical studies and systematic reviews.

The OSI model is widely recognised as an abstract and challenging concept for undergraduate computing students. A recent study by San Martín, Manzano, and Camargo (2025) notes that "abstract concepts like software design patterns and the OSI model often pose challenges for engineering students". The layered architecture, protocol mappings, and encapsulation processes require high levels of abstraction, making it difficult for students to form accurate mental models. Students often struggle to differentiate between layers, understand the purpose of each layer, and apply the model to real-world networking scenarios. These conceptual barriers contribute directly to poor academic performance in networking courses.

Empirical data from OSI-related instruction confirms that students frequently underperform on assessments involving the OSI model. The dataset accompanying the study "Do Students Learn Better Together?" includes raw assessment data from two undergraduate cohorts, showing significant variation and generally low individual quiz scores related to OSI content. These findings suggest that traditional instructional methods may not sufficiently support comprehension of the model's layered structure. Performance issues are often linked to: Misconceptions about layer functions, Confusion between OSI and TCP/IP models, Difficulty applying theoretical concepts to practical tasks, and Fragmented understanding of encapsulation and decapsulation. These challenges indicate that students require more structured, interactive, and collaborative learning approaches to improve performance.

Student attitudes play a critical role in shaping learning outcomes. A systematic review by Mashwama et al. (2025) emphasises that negative or disengaged attitudes hinder academic progress and comprehension across subjects. When applied to networking education, this suggests that students' perceptions of the OSI model, often viewed as overly theoretical, can significantly impact their motivation and performance. Common negative attitudes toward the OSI model include: perceived irrelevance: students may not see the immediate practical value of memorising layers; low self-efficacy: early struggles with abstraction reduce confidence; anxiety and frustration: difficulty understanding the model leads to avoidance behaviours; preference for hands-on learning: students often prefer practical networking tasks over conceptual frameworks. These attitudes create a feedback loop in which poor understanding leads to negative perceptions, which in turn further reduce engagement and performance.

2 Literature Review

Computing education is critical for enabling students to excel in a technologically driven world. Nevertheless, the way in which computing is taught in classroom settings has been unable to overcome the existing disparity in learning outcomes, most particularly in multilingual, multicultural, or constrained learning environments (Jacob et al., 2022; Jacob & Warschauer, 2024; Oladejo et al., 2023). Studies indicate that most computer science classrooms operate in a technocentric style, oriented toward the technical and drill-skills-oriented paradigm without an appropriate integration with sound theoretical foundations in pedagogy, thereby hindering improvements in both intellectual achievement and attitudes toward computer science disciplines (Oladejo et al., 2023).

Meanwhile, there emerges the increasing role of Artificial Intelligence in Education as a potential disruptor for the design of instruction and the processes of learning. These are the promising uses of artificial intelligence: generative technology, intelligent tutoring systems, or adaptive learning systems with significant potential in providing personalised feedback, improving the scaffolding of difficult tasks, as well as the adaptation of the level of content to the needs of the learners (Ayeni et al., 2024; Dey, 2025; Mahmoud & Sørensen, 2024; Merino-Campos, 2025). However, if there are designs that lack cultural responsiveness, these systems may work to amplify the problem of inequity, particularly in serving learners from backgrounds that are not dominant in the language of instruction or cultural contexts (Hariyanto et al., 2025; Kayyali, 2025; Mariyono & Abror, 2024). These challenges are further evident in multilingual environments where there is diversity in language, including socio-cultural diversity (Dodoo et al., 2025; Jacob et al., 2022; Prather et al., 2025). Though AI applications have been prevalent in second-language learning and adaptive systems, most of this research for second-language acquisition is English-centric or monolingual, providing meagre help for students with multiple language identities (Dodoo et al., 2025; Prather et al., 2025; Vogel et al., 2020). Additionally, the existing body of research on AI-enhanced pedagogy and engagement in computer education shows a more mixed consensus among educators and students concerning the integration of AI with teaching and learning in computer education, with apprehensions about appropriate utilisation, fairness, and effective engagement with educational objectives (Prather et al., 2025). The implications of the barriers posed by the differences in linguistics in AI for non-native English speakers could be the reason for the mixed consensus regarding the integration of AI with education in the literature consulted.

Culturally responsive methods such as the Culturo-Techno-Contextual Approach (CTCA), for example, are emerging within the world of education research. These methods involve intentionally connecting students' cultures, indigenous knowledge, and experiences to how we deliver instruction. Research has indicated that the Culturo-Techno-Contextual Approach can strengthen conceptual understanding, improve retention, and reduce the abstract concepts of ICT by making them more relevant through connecting them to cultural references. However, despite evidence of its effectiveness on thinking skills as well as engagement, there remains a dearth of literature that connects the Culturo-Techno-Contextual Approach or cultured approaches to AI technology in computing education.

We are faced with the intersection of the following three trends: the rise of multilingual learners, the capabilities of adaptive artificial intelligence, and pedagogy that is contextually rooted. These meet the critical needs for the exploration of the potential of multilingual, CTCA-based, artificial intelligence-enhanced instruction in regard to both attitudinal (motivation, computing Selbstwirkung, perceptions of computing) and achievement (computational knowledge gains, computing performance) outcomes in mobile computing contexts. Mobile computing is significant in regions with less computing infrastructure but with widely adopted smartphones, allowing adaptive systems to align their resources with the languages and cultures of those regions. Finally, the potential of such a hybrid framework for CTCA, artificial intelligence, and multilingual supports would enable the work presented in this special issue to offer theoretically grounded, empirical insights into the study of computing education with equity in mind.

Instructional Approaches and Their Impacts

Traditional lecture-based instruction has been criticised for failing to promote deep understanding of the OSI model. San Martín et al. (2025) argue that traditional methods "may fall short in promoting deep understanding and individual accountability" when teaching abstract concepts like the OSI model.

Collaborative learning approaches, such as the Aronson Jigsaw method, have demonstrated potential in improving both performance and attitudes. The study found that structured peer teaching improved engagement and comprehension of OSI concepts. Students working in groups developed stronger mental models and demonstrated improved assessment outcomes compared to those taught through traditional methods. These findings suggest that pedagogical strategies emphasising collaboration, active learning, and shared responsibility can mitigate negative attitudes and improve performance.

The OSI model remains a challenging topic for many students in computer networking courses. Poor performance and negative attitudes are closely linked to the abstract nature of the model and the instructional approaches commonly used. Emerging research suggests that collaborative, student-centred pedagogies can significantly improve understanding and engagement. Future work should explore how adaptive learning technologies, simulations, and peer-learning frameworks can further support student mastery of the OSI model.

Culturo-Techno-Contextual Approach (CTCA)

The Culturo-Techno-Contextual Approach (CTCA) is an instructional strategy developed by Okebukola to address persistent learning difficulties and poor student outcomes in science, mathematics, and technology-related subjects, particularly in African contexts. CTCA integrates three core components: culture, technology, and context, intending to make learning more meaningful and relatable to learners (Okebukola, 2015).

According to Okebukola (2021), CTCA emphasises the use of learners' cultural experiences, indigenous knowledge systems, familiar technologies, and immediate environments as entry points for teaching abstract concepts. This approach contrasts with conventional teaching methods that often present content in isolation from students' lived realities, thereby limiting comprehension and engagement.

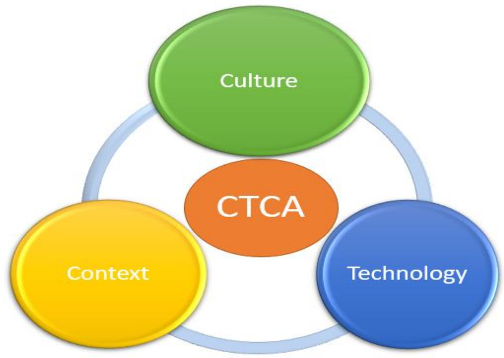

Figure 1 Components of CTCA

CTCA and Students' Academic Achievement

Empirical studies consistently demonstrate that CTCA has a significant positive effect on students' academic achievement. Several quasi-experimental studies conducted in Nigerian secondary schools reveal that students exposed to CTCA outperform their counterparts taught using traditional lecture methods.

Agbanimu, Okebukola, Oladejo, Gbeleyi, and Umar Adam (2025) investigated the effectiveness of CTCA in teaching computer studies concepts such as algorithms and flowcharts. Their findings revealed a statistically significant difference in achievement scores in favour of students taught using CTCA. The researchers attributed this improvement to the contextualisation of abstract concepts through familiar cultural practices and everyday technological applications.

Similarly, Onowugbeda et al. (2024) examined the effect of CTCA on students' achievement and retention in biology. The study reported that students taught using CTCA demonstrated higher post-test scores and better retention of concepts compared to those taught using conventional instructional methods. This suggests that CTCA enhances deeper cognitive processing and long-term understanding.

A systematic review conducted by Oladejo and Okebukola (2025) further reinforced these findings. Reviewing multiple CTCA-based studies across STEM subjects, the authors concluded that CTCA consistently leads to improved academic achievement, particularly in topics traditionally perceived as difficult by students.

CTCA and Students' Attitude Toward Learning

In addition to academic achievement, students' attitudes toward learning play a crucial role in determining educational success. Research indicates that CTCA positively influences students' attitudes by increasing interest, motivation, and confidence in learning.

Okebukola (2015) noted that when students see their culture and daily experiences reflected in classroom instruction, they develop a sense of ownership and relevance, which positively affects their attitude toward learning. This view is supported by Agbanimu et al. (2025), who found that students taught using CTCA expressed greater enthusiasm and participation during lessons compared to those taught using traditional methods.

Onowugbeda et al. (2024) also reported that CTCA improved students' attitudes toward biology by reducing fear and anxiety associated with abstract scientific concepts. Students exposed to CTCA described lessons as more engaging, practical, and easier to understand, leading to increased motivation and positive learning dispositions.

Furthermore, Oladejo and Okebukola (2025) observed that CTCA promotes positive learner attitudes by encouraging interaction, collaboration, and critical thinking. These attitudinal improvements are important because positive attitudes have been shown to correlate strongly with higher academic achievement and sustained engagement in learning tasks.

Theoretical and Philosophical Frameworks

Vygotsky's Theory of Social Constructivism

Lev Vygotsky's theory of social constructivism, also known as sociocultural theory, is centred on the idea that cognitive development is a social process. In this framework, peers, parents, caregivers, and the broader cultural and societal environment play significant roles in shaping a child's learning. Vygotsky (1962) contended that children actively construct their own knowledge through interaction with others and by engaging in problem-solving activities.

Central to Vygotsky's theory is the concept of the Zone of Proximal Development (ZPD), which refers to the gap between a learner's current level of understanding and their potential development when guided by a more knowledgeable individual. The ZPD illustrates the importance of scaffolding in education—where learners are supported in acquiring new knowledge by teachers, peers, or caregivers until they are able to master the concepts independently.

Vygotsky's theory suggests that students learning complex concepts, such as those related to information security, may not initially grasp the material fully. However, with the guidance of an experienced instructor or peer, they can gradually build their understanding and develop critical thinking skills. This approach emphasises the value of social interaction in enhancing academic performance, as students learn not only from their own experiences but also from their interactions with others.

Ausubel's Theory of Advanced Organisers

David Ausubel's theory of advanced organisers (1962) focuses on the cognitive processes involved in learning and memory. Advanced organisers are instructional tools that provide students with a broad conceptual framework before learning new material. These organisers help students connect new information to what they already know, thereby facilitating deeper understanding and retention of knowledge.

According to Ausubel, meaningful learning occurs when students are able to relate new information to existing knowledge structures. Advanced organisers provide the scaffolding necessary for this process, ensuring that students can integrate new material into their pre-existing cognitive frameworks. In this way, students engage in active learning, rather than simply memorising facts. Ausubel's theory stresses the importance of providing students with a global perspective on the subject matter, which enables them to see how new concepts fit into the broader context of what they have already learned.

Kwame Nkrumah's Ethnophilosophy

Kwame Nkrumah first introduced the concept of "ethno-philosophy," a term later further developed and popularised by Pauline Houtondji, which synthesises elements of ethnography and philosophy. Ethnophilosophy is principally concerned with examining indigenous philosophical systems by foregrounding the collective worldviews, mythologies, and folklore inherent to African cultures. This approach underscores the intellectual and cultural autonomy of African societies, positing that African thoughts and philosophical traditions developed independently and possess intrinsic value equivalent to that of Western philosophical paradigms (Oko & Ogbodo, 2022).

In essence, Nkrumah's ethnophilosophy articulates a framework wherein the worldview of ethnic Africans is not only examined as a distinctive intellectual tradition but also appreciated for its ability to provide profound insights into the human condition. This framework is pivotal to the Culturo-Techno-Contextual Approach (CTCA 2.0), as it leverages indigenous beliefs, epistemologies, and cultural practices to enrich scientific discourse and broader academic inquiry, thereby reaffirming that non-Western societies are capable of sophisticated and nuanced modes of thought.

Multilingual Education

Multilingual education, defined as the use of two or more languages as media of instruction, has become a key focus of educational research due to its potential to enhance students' academic achievement and attitudes toward learning. It encompasses mother-tongue instruction, bilingual programmes, and additive multilingual approaches, where learners develop skills in multiple languages while engaging with academic content (Cummins, 2000; UNESCO, 2016). The review provides the foundation for understanding how multilingual approaches can influence learning outcomes and learner engagement.

Multilingual education is grounded in theories of cognitive development, language transfer, and social identity. Cummins' Interdependence Hypothesis posits that skills acquired in a first language (L1) transfer to additional languages (L2), enhancing overall academic competence (Cummins, 2000). Similarly, García and Wei (2014) emphasise translanguaging, which allows learners to utilise their full linguistic repertoire in classrooms, fostering comprehension and engagement.

UNESCO (2016) underscores the importance of mother-tongue-based multilingual education (MTB-MLE), particularly in early schooling, to establish foundational literacy and promote continuity in learning. Instruction that begins in students' home language and progressively introduces additional languages is considered most effective for both cognitive and affective development.

Multilingual Education and Students' Academic Achievement

Research consistently demonstrates that multilingual education enhances academic achievement. Learners taught initially in their mother tongue perform better in literacy and numeracy compared to peers instructed exclusively in a second language (Heugh, 2011). For instance, dual-language programmes in Europe and North America have been associated with higher achievement in both language proficiency and subject-specific content, demonstrating that bilingual learners often outperform monolingual peers (Thomas & Collier, 2012).

Bilingualism and multilingualism also contribute to metalinguistic awareness, problem-solving, and cognitive flexibility, which further support academic success (Bialystok, 2017). These cognitive advantages translate into improved performance in reading comprehension, mathematics, and other disciplines where higher-order thinking is required.

Longitudinal studies confirm that students in well-implemented multilingual programmes maintain higher academic performance over time. August and Shanahan (2006) found that learners in extended bilingual programmes consistently achieved better outcomes in literacy and mathematics than those in transitional bilingual or English-only programmes. These findings suggest that sustained multilingual education is particularly beneficial for building deep, transferable knowledge.

Multilingual Education and Students' Attitude Toward Learning

Multilingual education has been linked to more positive student attitudes toward learning. Ball (2011) notes that learners instructed in languages they understand demonstrate increased confidence, reduced anxiety, and greater class participation. Similarly, Alexander (2000) reports that mother-tongue-based instruction enhances motivation, engagement, and persistence in learning tasks.

Research in Africa and South Asia indicates that students perceive education more positively when their home languages and cultures are incorporated into learning materials, which increases their intrinsic motivation and willingness to engage with academic content (Bourdillon et al., 2010; Nishimura, 2009).

In addition to cognitive benefits, multilingual education affirms learners' cultural identities, fostering positive attitudes toward both schooling and self-expression (Skutnabb-Kangas, 2000). Students who perceive their languages and cultures as valued are more likely to develop a positive self-concept and maintain interest in learning over time.

3 Methodology

Research Design

This study employed a pre-test–post-test, quasi-experimental design with four intact groups. A fully randomised controlled trial was considered but deemed methodologically inappropriate for the current context, as the core pedagogical framework under investigation, the Culturo-Techno-Contextual Approach (CTCA), is fundamentally designed to leverage and function within existing, communal classroom ecologies. Randomising individual students would have dismantled these natural social learning units and compromised the ecological validity of the intervention. Consequently, randomisation was applied at the class level. The independent variable was the pedagogical and linguistic mode of instruction, operationalised across four distinct conditions: a traditional lecture-based Control Group (CG); a CTCA group supported by a monolingual, English-only AI chatbot (Harlybot), designated CTCA-M; a CTCA group supported by Harlybot operating under a calibrated strategic multilingual protocol (80% English, 10% Nigerian Pidgin, 10% Yoruba), designated CTCA-SM; and a CTCA group supported by Harlybot operating in a predominantly Pidgin and Yoruba mode, designated CTCA-HM. The primary dependent variables were learning achievement (retention), attitudinal disposition towards the subject matter, and critical thinking performance specific to the Open Systems Interconnection (OSI) model within Mobile and Adaptive Systems.

Participants and Context

The participant pool comprised 75 second-year undergraduate students enrolled in Computer Science programmes across four universities in Southwestern Nigeria. The institutions included three state-owned universities and one private university, providing a mix of institutional contexts. Participants were drawn from four intact classes, which were randomly assigned to the four experimental conditions. This resulted in the following distribution: Control Group (CG, n = 13), CTCA-Monolingual (n = 15), CTCA-Strategic Multilingual (n = 19), and CTCA-Heavy Multilingual (n = 28). The unequal sample sizes were a direct reflection of natural class enrollment figures and were addressed in the statistical analysis phase using covariance techniques. All instructional content was rigorously adapted from the standard university course module, "The OSI Model in Mobile Communication," ensuring curricular alignment and relevance.

Intervention Procedure

The instructional intervention spanned a period of six weeks for all groups, with identical core content on Mobile and Adaptive Systems covered. The OSI model and the conceptually challenging processes of encapsulation and de-encapsulation received intensive focus during Weeks 3 and 4. The critical difference across conditions lay in the enactment of the Culturo-Techno-Contextual Approach 2.0 (Okebukola, 2020) and the linguistic behaviour of the supporting AI agent, Harlybot. All CTCA conditions adhered strictly to the framework's validated seven-step sequence.

Instruction began with **Step 01** (Cultural Preview & Technology Hook), where students, before class, used internet-enabled devices to review curated YouTube videos on data transmission. They subsequently completed a pre-lesson assignment distributed via WhatsApp, which required them to identify and describe a local cultural practice or ritual that could serve as an analogy for layered data communication (e.g., a message passing through multiple village elders). **Step 02** (Scaffolding via Peer Presentation) commenced each classroom session, with students presenting and debating their cultural analogies in small groups. This phase served as the primary site for organic, student-led code-switching into Nigerian Pidgin and Yoruba within the two multilingual conditions.

This was followed by **Step 03** (Contextualisation by Instructor), where the lecturer formally introduced the technical OSI concepts, deliberately weaving in the students' own analogies and supplementing them with immediate, context-aware examples from the Nigerian digital landscape. The instructor's linguistic responses mirrored the tone set by student presentations, thereby reinforcing the designated linguistic ecology. **Steps 04 & 05** (Reflection and Consolidation) involved the lecturer explicitly reconciling the initial cultural hooks with the formal technical definitions, directly addressing persistent misconceptions about encapsulation and de-encapsulation. This phase constituted a second strategic site for multilingual reinforcement and conceptual solidification.

Each instructional session concluded with **Steps 06 & 07** (Technology Integration & Extension), which involved pushing a concise summary of key takeaways to students via WhatsApp and activating access to Harlybot. The chatbot functioned not as a replacement for human instruction but as a persistent, on-demand conversational partner for individualised clarification, practice, and extension of the lesson content, thereby fully realising the technological pillar of the CTCA framework.

Harlybot Implementation and Linguistic Protocol

The chatbot's functionality was precisely tailored to each experimental condition. In the CTCA-M condition, Harlybot responded exclusively in formal academic English. In the CTCA-SM condition, it operated under the pre-defined 80-10-10 strategic protocol. Its baseline interaction was in formal English; however, upon algorithmic detection of a cognitive impasse signalled by two consecutive incorrect answers, a response latency exceeding 15 seconds, or an explicit "I don't understand" prompt, the agent would inject a single, culturally resonant explanatory analogy or rephrasing in either Nigerian Pidgin or Yoruba. Following this strategic code-switch, the conversation seamlessly reverted to English for further conceptual development. In the CTCA-HM condition, Harlybot operated in a dominant Pidgin/Yoruba mode, reflecting a pedagogical environment where the local languages served as the primary medium for conceptual exploration and support.

Intervention Fidelity

To ensure strict adherence to the CTCA pedagogical sequence across all facilitators, the research team utilised the validated CTCA 2.0 Classroom Observation Scale for weekly monitoring. Furthermore, Harlybot's adherence to its assigned linguistic thresholds (particularly the 80-10-10 rule) was continuously verified through automated analysis of conversation logs, ensuring the integrity of the experimental manipulation.

Instruments and Data Collection

Quantitative Measures

Three primary instruments were used for quantitative data collection. The Assessment of OSI-Model Proficiency (AOSIMP), a 40-item multiple-choice test, measured conceptual understanding and retention (KR-20 reliability = .91). The Attitude Towards OSI-Model Questionnaire (ATOSIQ), a 5-point Likert scale, gauged students' interest, perceived utility, and learning anxiety related to the topic. To assess higher-order reasoning, the Okebukola Critical Thinking Test (Owolabi & Oladejo, 2024 adaptation) was administered; this performance-based assessment presented a complex packet-tracing scenario requiring analytical reasoning, with an established inter-rater reliability of .94. All three instruments were administered as pre-tests one week before the intervention and as post-tests immediately following its conclusion in Week 6.

Qualitative Measures

A multi-modal qualitative approach was adopted to capture the experiential depth of the learning process. First, semi-structured interviews were conducted with a purposively selected subsample of 24 participants (six from each condition) immediately post-intervention. Selection criteria prioritised students who exhibited either marked improvement or persistent difficulty on the post-test, as well as those who were particularly vocal during sessions. Each 18–25 minute interview, conducted in the participant's preferred language mix, explored pivotal moments of conceptual breakthrough, the perceived role of multilingual analogies, and affective responses to the learning environment. Second, think-aloud protocols were audio-recorded while a subset of participants verbalised their problem-solving process during the OSI model packet-tracing task. Finally, one focus group discussion was held at each of the four participating institutions to capture collective perceptions and group dynamics.

Data Analysis

Quantitative Analysis

The quantitative data were analysed using a one-way Multivariate Analysis of Covariance (MANCOVA). The model included the post-test scores from the AOSIMP, ATOSIQ, and Critical Thinking Test as dependent variables, the experimental condition (CG, CTCA-M, CTCA-SM, CTCA-HM) as the fixed factor, and the corresponding pre-test scores as covariates. This approach controlled for baseline differences and increased the statistical power of the analysis. Following a significant omnibus MANCOVA result, follow-up univariate ANCOVAs were conducted for each dependent variable. Where significant main effects were found, Scheffé post-hoc comparisons were employed to pinpoint specific differences between the four instructional conditions. All analyses utilised Type III sums of squares to appropriately handle the unequal group sizes. Effect sizes were calculated and reported as partial eta-squared (η^2p) to indicate the practical significance of the findings.

Qualitative Analysis

All qualitative data, including interview transcripts, think-aloud protocols, and focus group notes, were subjected to a rigorous reflexive thematic analysis following the six-phase framework established by Braun and Clarke (2022). The process began with deep familiarisation through repeated reading of the transcripts. Initial codes were then generated inductively from the data, focusing on participant experiences with language, culture, and conceptual understanding. These codes were subsequently collated and reviewed to form potential themes, which were rigorously checked against the entire dataset for consistency and prevalence. The final themes were clearly defined, named, and integrated into a coherent analytic narrative that directly addressed the research questions. This method was selected for its theoretical flexibility and its capacity to provide a rich, nuanced, and complex account of how the multilingual CTCA intervention was experienced across different learning contexts.

Ethical Considerations

The study received full ethical approval from the Lagos State University Research Ethics Committee. Before participation, all students provided written informed consent after a detailed briefing on the study's aims, procedures, and their rights. These rights included guarantees of anonymity, confidentiality of all data, secure data storage, and the unequivocal right to withdraw from the study at any point without academic penalty. All audio recordings were transcribed verbatim by trained research assistants fluent in the relevant languages, and the original recordings were securely destroyed following transcription to further protect participant confidentiality.

Method of Data Analysis and Assumption Checks

Before carrying out the Multivariate Analysis of Covariance (MANCOVA), it was necessary to test the data to see if it fulfilled the parametric assumptions needed in the statistical test. The Shapiro-Wilk tests conducted to test the normality assumption showed that the post-test scores against the Assessment of OSI-Model Proficiency (AOSIMP) and Attitude Towards OSI-Model Questionnaire (ATOSIQ) were not normally distributed. Nonetheless, considering the tolerable conditions under which the normal assumption is violated in MANCOVA tests when the group sample sizes are nearly equal in size, it was acceptable to move on with the test.

Further tests regarding assumptions held that both AOSIMP and ATOSIQ passed Levene's test for equality of variances, constituting confirmation that the variances of errors across the groups were homogeneous. Furthermore, the Box's M-test results appeared to be non-significant; hence, the results confirmed that the variance and covariance matrices for the groups are homogeneous. These pieces of evidence collectively implied that the departure from normality notwithstanding, the assumptions for conducting MANCOVA analysis had been met.

4 Results and Interpretation

Hypothesis One

There will be no statistically significant difference in post-test achievement (retention) scores among students taught using the traditional lecture method, monolingual Harlybot-CTCA, and 80–10–10 multilingual Harlybot-CTCA, after controlling for pre-test achievement scores.

Results

Students' achievement and retention were measured using the Assessment of OSI-Model Proficiency (AOSIMP). Descriptive statistics presented in Table 1 indicate observable differences in mean post-test achievement scores across instructional groups. Students exposed to CTCA-based instruction recorded higher mean scores than those taught using the traditional lecture method. Specifically, the monolingual CTCA group achieved the highest mean score (M = 66.80, SD = 8.74), followed by the heavy multilingual CTCA group (M = 63.57, SD = 11.53) and the strategic multilingual CTCA group (M = 62.53, SD = 12.09). The control group recorded the lowest mean score (M = 56.92, SD = 17.18).

Table 1 Descriptive Statistics of Post-test Achievement and Attitudinal Scores by Instructional Modes

Variables	Group	Mean	Std. Deviation	N
Assessment of OSI-Model Proficiency (AOSIMP) Post-test for Achievement	Control Group	56.92	17.18	13
	CTCA-Heavy Multilingual	63.57	11.53	28
	CTCA-Monolingual	66.80	8.74	15
	CTCA-Strategic Multilingual	62.53	12.09	19
	Total	62.80	12.49	75
Attitude Towards OSI-Model Questionnaire (ATOSIQ) Post-test	Control Group	3.4423	.42	13
	CTCA-Heavy Multilingual	2.5839	.21	28
	CTCA-Monolingual	2.0767	.09	15
	CTCA-Strategic Multilingual	2.4132	.37	19
	Total	2.5880	.52	75

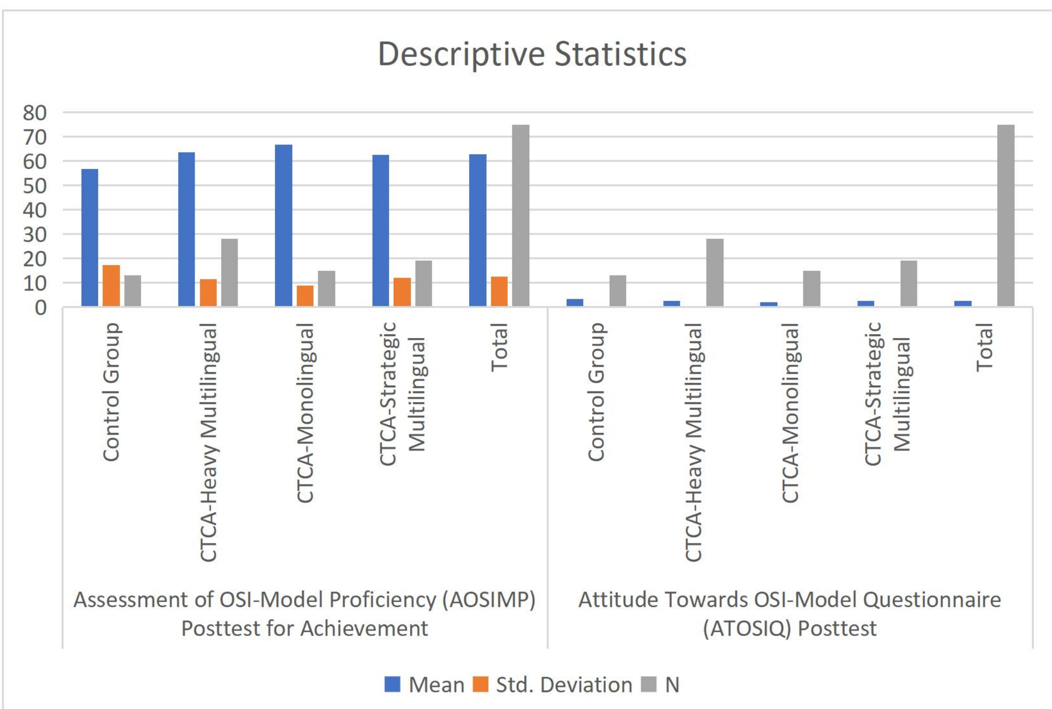

Figure 2 The descriptive statistics of the dependent variables

A Multivariate Analysis of Covariance (MANCOVA) was conducted to examine the effect of instructional mode on students' learning outcomes while controlling for pre-test achievement scores. As shown in Table 2, the multivariate test revealed a statistically significant overall effect of instructional group on the combined dependent variables, Wilks' Λ = .129, $F(6, 136) = 40.559$, $p < .001$, partial $\eta^2 = .641$. This result indicates that instructional condition accounted for a substantial proportion of variance in students' combined learning outcomes.

Table 2 Multivariate Analysis of Covariance (MANCOVA) Results for Instructional Language Mode on Cognitive Outcomes

	Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Pillai's trace	.94	20.20	6.00	138.00	.00	.47

Given the significant multivariate effect, follow-up univariate ANCOVA analyses were conducted. Results from the Tests of Between-Subjects Effects in Table 3 showed that the effect of instructional group on post-test achievement (AOSIMP) was not statistically significant after controlling for pre-test scores, $F(3, 69) = 2.49$, $p = .07$, partial $\eta^2 = .10$. Although the effect size suggests a small-to-moderate practical influence, the observed difference did not reach the conventional .05 level of statistical significance.

Table 3 Univariate ANCOVA Results for Post-test Achievement and Attitudinal Scores

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Group	AOSIMP Post-test	991.53	3	330.51	2.49	.07	.10
	ATOSIQ Post-test	26.72	3	8.91	130.87	.00	.85

Interpretation

The findings indicate that while CTCA-based instructional modes, particularly the monolingual CTCA approach, were associated with higher adjusted mean achievement scores, these differences were not statistically significant when prior achievement was controlled. This suggests that students' post-test achievement and retention in the OSI model were strongly influenced by their baseline knowledge, and that the instructional modes did not differentially affect achievement within the duration of the intervention.

Accordingly, Null Hypothesis One (H_{01}) was not rejected, indicating that there was no statistically significant difference in post-test achievement (retention) scores among students taught using the traditional lecture method, monolingual CTCA, and multilingual CTCA after accounting for pre-test achievement.

Hypothesis Two

There will be no statistically significant difference in post-test attitude scores among the three instructional conditions, after controlling for pre-test attitude scores.

Results

Students' attitudes toward learning the OSI model were assessed using the Attitude Toward OSI-Model Questionnaire (ATOSIQ). Descriptive statistics in Table 1 reveal marked differences across instructional groups. Students taught using CTCA-based approaches demonstrated more positive attitudes than those in the control group. The monolingual CTCA group recorded the most favourable attitude scores ($M = 2.08$, $SD = 0.09$), followed by the strategic multilingual CTCA group ($M = 2.41$, $SD = 0.37$) and the heavy multilingual CTCA group ($M = 2.58$, $SD = 0.21$). In contrast, the control group recorded the least favourable attitude scores ($M = 3.44$, $SD = 0.42$). Lower mean scores on the ATOSIQ indicate more positive attitudes.

Follow-up univariate ANCOVA results showed a statistically significant effect of instructional group on post-test attitude after controlling for pre-test attitude scores, $F(3, 69) = 130.87$, $p < .001$, partial $\eta^2 = .851$. The magnitude of the effect size indicates an extremely large practical effect, with instructional condition accounting for over 85% of the variance in students' attitudinal outcomes.

Interpretation

The results provide strong evidence that instructional mode significantly influenced students' attitudes toward learning the OSI model. CTCA-based approaches, especially the monolingual CTCA strategy, produced substantially more positive attitudinal outcomes than the traditional lecture method. The very large effect size underscores the practical and educational significance of CTCA-driven instruction in shaping learners' affective dispositions.

Consequently, Null Hypothesis Two (H_{02}) was rejected, indicating that statistically significant differences exist in students' post-test attitude scores across instructional conditions, even after controlling for initial attitudes.

5 Discussion

The results revealed a significant and large-effect advantage for all CTCA-based instructional modes in fostering positive attitudes toward learning, while their effect on achievement (retention), though descriptively positive, did not reach statistical significance.

The powerful positive effect of CTCA on attitudes aligns with constructivist and self-determination theories (Deci & Ryan, 2000; Vygotsky, 1978). CTCA's emphasis on collaborative learning, cultural grounding, and technology integration likely enhanced students' sense of autonomy, relatedness, and competence key drivers of intrinsic motivation and positive affect (Ryan & Deci, 2020). This finding resonates with studies on active learning, which consistently report improved student engagement and satisfaction compared to passive lecture formats (Freeman et al., 2014).

The non-significant finding for achievement, despite higher mean scores in CTCA groups, invites a nuanced interpretation. First, the high variance in the control group's scores (SD = 17.18) may have reduced statistical power to detect a significant effect. More importantly, achievement, particularly retention of technical networking concepts like the OSI model, may require longer intervention periods or more frequent reinforcement for differences to solidify and become statistically detectable (Sweller et al., 2011). This interpretation is supported by the significant influence of the pre-test covariate, highlighting the strong role of prior knowledge. The result partially contrasts with meta-analyses showing significant achievement gains from active learning (Theobald et al., 2020) but aligns with literature suggesting that gains in complex cognitive domains may manifest first in affective domains before translating into significant test score differences (Pekrun, 2006).

Interestingly, the monolingual CTCA mode yielded the best outcomes on both measures. This suggests that for this specific technical content, clarity and consistency in the language of instruction (English), when delivered within an engaging, culturally contextualised pedagogy like CTCA, may have optimised cognitive load and attitude simultaneously (Kalyuga, 2011). The multilingual variations, while still far superior to the traditional method, may have introduced additional processing demands for mastering highly standardised terminology, potentially attenuating the achievement effect.

6 Conclusion

This study examined the effects of traditional lecture and CTCA-based instructional methods, including monolingual and multilingual approaches, on students' achievement and attitudes toward learning the OSI model. The findings revealed a gap between cognitive and affective outcomes: while CTCA-based methods did not significantly improve achievement, they produced a very large positive effect on students' attitudes.

The results highlight CTCA's strength in fostering affective engagement through culturally relevant learning, collaboration, and supportive technology. The absence of significant achievement gains reflects the complexity of abstract networking concepts and suggests that attitudinal change may precede cognitive improvement. Longer implementation periods may therefore be needed to translate positive attitudes into measurable achievement outcomes.

Recommendation

Based on the findings, educators and curriculum developers should adopt CTCA for teaching abstract computing concepts, while integrating AI tools as supportive resources for clarification and scaffolding. Strategic multilingual practices should be applied where they enhance understanding, and longer CTCA implementation should be encouraged to support achievement gains. Teacher training should incorporate CTCA and culturally responsive AI pedagogy, while policymakers should promote inclusive digital innovations that integrate culture, technology, and context, particularly in multilingual learning environments.

Practical and Social Implications

The findings suggest that AI-supported Culturo-Techno-Contextual Approach (CTCA 2.0) can promote more engaging, inclusive, and culturally responsive computing education by improving students' attitudes toward learning abstract concepts. Integrating AI, multilingual support, and culturally relevant instructional strategies into computing curricula can enhance learner motivation, confidence, and participation while fostering equitable access to quality education. The adoption of this approach by educators, institutions, and policymakers may strengthen digital inclusion, broaden participation in STEM, and contribute to the development of a diverse, technologically skilled workforce capable of supporting sustainable socioeconomic development.

Study Limitations

Several limitations qualify these findings. First, the sample size was modest (N=75) and from a specific context, limiting generalisability. Second, the quasi-experimental design means that despite statistical control for pre-tests, unmeasured confounds (e.g., teacher effects, group dynamics) could influence results. Third, measurement constraints exist: the achievement test may not have fully captured deeper conceptual understanding or long-term retention. Finally, the intervention duration may have been insufficient for achievement differences to reach statistical significance.

Future Research Directions

Future research should further examine the effectiveness of CTCA through large-scale randomised controlled trials and longitudinal studies that explore whether changes in learners' attitudes translate into sustained achievement gains. Researchers should also investigate discourse-specific language strategies within CTCA across different domains, including conceptual and procedural areas of computing. Additionally, qualitative and mixed-method approaches are encouraged to provide deeper insights into learners' cognitive and affective experiences during CTCA-based instruction.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The author declares no conflicts of interest

Declaration of Use of Generative AI

AI tools were used only for grammar and formatting. No part of the study's methods, analysis, or results was generated by AI. The authors take full responsibility for the work.

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