

Effects of AI-Driven Real-Time Captioning as an Orthographic Scaffold for Literacy Acquisition Among Deaf Learners in Plateau State, Nigeria

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Abstract

The literacy gap between deaf and hard-of-hearing (DHH) learners and hearing peers remains crucial in resource-constrained settings like Plateau State, Nigeria. Although human sign language interpretation gives conceptual access, DHH learners sometimes fail to develop direct orthographic representations of difficult English vocabulary due to fast fingerspelling and visual fatigue. This study examined AI-driven real-time captioning as a collaborative orthographic scaffold alongside human sign language interpreters. Using a quantitative quasi-experimental pretest-posttest control group design with delayed retention, 30 Primary Five pupils at Plateau State School for the Deaf, Bassa, were cluster-randomised into two intact groups: Experimental (AI captioning + sign interpretation; n=15) and Control (sign interpretation only; n=15). The eight-week intervention includes pretest, immediate posttest, and four-week delayed retention evaluation. Data were obtained using a validated 40-item English Literacy and Vocabulary Assessment (ELVA) and evaluated with independent-samples t-tests and ANCOVA. The Experimental Group attained considerably better posttest scores ($M=74.20$, $SD=6.85$) than the Control Group ($M=58.40$, $SD=7.92$), $t(28)=5.84$, $p<0.001$, Cohen's $d=2.13$. ANCOVA confirmed a substantial intervention effect, $F(1,27)=38.65$, $p<0.001$, partial $\eta^2=0.589$, adjusting for pretest scores. Delayed retention was likewise considerably higher for the Experimental Group ($M=71.80$, $SD=7.10$) than the Control Group ($M=52.60$, $SD=8.15$), $t(28)\approx 6.88$, $p<0.001$, Cohen's $d\approx 2.51$. Technical evaluation recorded an average Word Error Rate of 8.4% employing edge-computing hardware and FM lapel mics, circumventing internet instability. Findings imply simultaneous visual-verbal captioning and visual-nonverbal signing increase orthographic-lexical mapping without replacing sign language. Recommendations address policy, edge-hardware adoption, and teacher ICT competence training in Nigerian special schools.

Keywords: Deaf Education; AI Real-Time Captioning; Orthographic Scaffolding; Literacy Acquisition; Quasi-Experimental Study; Nigerian Special Education

Introduction

The acquisition of functional literacy is a foundational prerequisite for academic achievement, economic self-sufficiency, and social inclusion. However, a profound and persistent literacy gap exists globally between deaf and hard-of-hearing (DHH) learners and their hearing peers (Marschark and Knoors, 2020). In developing nations such as Nigeria, this disparity is particularly acute due to systemic resource constraints, limited access to specialised instructional technology, and broader socio-economic challenges in special education infrastructure (Ademokoya, 2021).

For hearing children, reading development relies heavily on an auditory-phonological loop through which printed orthographic symbols map onto pre-established spoken-language sounds encountered through years of direct acoustic exposure. Conversely, DHH pupils, such as those attending the Plateau State School for the Deaf, Bassa, interact with written English as an essentially visual-graphic system disconnected from spoken phonology. Consequently, DHH learners must construct direct visual-orthographic mappings to semantic meaning, a cognitive process requiring intensive, explicit, and sustained visual print exposure paired with clear contextual definitions (Marschark and Knoors, 2020).

In Nigerian special schools, instruction for DHH pupils is primarily facilitated through human sign language interpreters utilising Nigerian Sign Language (NSL) or Signed Exact English (SEE). While human interpretation provides indispensable access to conceptual knowledge, it may present challenges when introducing specialised, low-frequency, or abstract English vocabulary. When presenting new technical terms, interpreters may rely on fingerspelling chains, spelling words letter-by-letter through dynamic hand shapes, or conceptual approximations. Rapid fingerspelling requires pupils to visually decode letters in fluid motion and may increase visual-attentional demands (Meade, 2022).

Advances in Artificial Intelligence (AI) and Automatic Speech Recognition (ASR) present novel opportunities to bridge this orthographic gap. When real-time AI-generated captions are streamed simultaneously alongside live sign language interpretation, DHH learners receive dual-modal visual input: visual-nonverbal signing for conceptual understanding and visual-verbal text for precise orthographic representation (Yoon and Kim, 2021). Rather than replacing human sign language interpreters, AI captioning can function as a collaborative orthographic scaffold, providing an instantaneous visual representation of academic vocabulary.

Despite its theoretical potential, empirical research investigating the practical efficacy of AI captioning in Sub-Saharan African special education classrooms remains limited. Existing literature on speech-to-text technology predominantly originates from high-resource contexts featuring standardised accents, relatively controlled acoustic environments, and reliable digital infrastructure. These conditions differ substantially from Nigerian classrooms, where local accent variations, ambient noise, power interruptions, and unstable internet connectivity may

affect technological deployment. Therefore, an empirical investigation examining both the literacy effects and technical feasibility of AI captioning in a Nigerian special-school setting is warranted.

Purpose of the Study

The primary purpose of this study was to empirically evaluate the effect of AI-driven real-time captioning, used as a collaborative orthographic scaffold alongside human sign language interpretation, on the English literacy and vocabulary acquisition of Primary Five pupils at the Plateau State School for the Deaf, Bassa, Nigeria.

Research Objectives

Specifically, the study sought to:

1. determine the difference in posttest English literacy and vocabulary scores between pupils exposed to AI real-time captioning with human sign language interpretation (Experimental Group) and those exposed to human sign language interpretation only (Control Group);
2. assess the effect of the AI captioning intervention on pupil retention of low-frequency academic vocabulary over time; and
3. evaluate the technical accuracy, measured by Word Error Rate (WER), of edge-based AI speech-recognition software operating in a typical Nigerian deaf classroom environment.

Research Hypotheses

The following null hypotheses were tested at the .05 level of significance:

H01: There is no statistically significant difference in posttest English literacy and vocabulary acquisition scores between Primary Five deaf pupils exposed to AI real-time captioning alongside human sign language interpretation and those exposed to human sign language interpretation alone, when controlling for pretest achievement.

H02: There is no statistically significant difference in delayed posttest vocabulary retention scores between the Experimental Group and the Control Group.

Literature Review

The disparity in literacy levels between deaf and hard-of-hearing (DHH) students and their hearing counterparts continues to be a significant worldwide issue, especially pronounced in resource-limited environments such as Nigeria (Ademokoya, 2021; Marschark and Knoors, 2020). DHH students are required to establish direct visual-orthographic connections to semantic meaning, given that written English functions as a visual-graphic system apart from spoken phonology (Marschark and Knoors, 2020). Although human sign language interpretation offers crucial conceptual understanding, swift fingerspelling for unknown terms may heighten visual-

attentional requirements (Meade, 2022). The advent of AI-generated captioning presents a prospective cooperative orthographic framework, delivering concurrent visual-verbal text in conjunction with visual-nonverbal signing (Paivio, 1991; Yoon and Kim, 2021).

Contemporary Nigerian research has commenced investigating the incorporation of AI in language instruction. Akinsulire et al. (2025) analyzed the application of AI technology in language education, whereas Aliyu et al. (2026) explored the impact of AI-assisted teaching on the academic performance of students with hearing disabilities. Olatunji and Olatunji-Olawepo (2025) evaluated the attitudes of AI sign language interpretation tools among Nigerian children with hearing disabilities and their educators. Olagoke and Adanlawo (2025) illustrated AI-based methodologies that improve vocabulary acquisition in multilingual educational settings. Moreover, Ubur (2026) investigated AI-enhanced emotional captioning to promote equitable STEM opportunities for DHH students, while Apata (2026) examined digital narratives and multimodal representations as innovative avenues in language advancement.

Theoretical grounds for this work synthesise Dual Coding Theory (Paivio, 1991), Cognitive Load Theory, and Universal Design for Learning. Paivio's model endorses concurrent visual-verbal and visual-nonverbal representations, but cognitive load factors indicate that consistent captions may alleviate the burdens linked to ephemeral fingerspelling. Stinson and Cawthon (2015) underlined curriculum accessibility for DHH learners, and Matthew (2020) highlighted caption accuracy as crucial to educational value of speech-to-text systems.

Despite theoretical promise, empirical research on AI captioning in Sub-Saharan African special education remains scarce. Existing material largely stems from high-resource environments with uniform accents and reliable infrastructure—conditions differing greatly from Nigerian classrooms (Yoon and Kim, 2021). Muhoozi (2025) and Madhu (2025) addressed AI-powered multilingualism and equity concerns, however localised evidence is scant. Milaham (2020) documented narrative storytelling practices for hearing-impaired pupils in Plateau State, offering regional context. Similoluwa et al. (2025) evaluated AI's involvement in managing handwriting and spelling issues among kids with learning challenges, suggesting broader applicability.

This work addresses the highlighted gap by empirically testing AI real-time captioning as an orthographic scaffold specifically inside Nigerian deaf education, examining both literacy effects and technological feasibility in actual classroom situations.

Theoretical Framework

This study was grounded in a synthesis of three complementary theoretical perspectives: Dual Coding Theory, Cognitive Load Theory, and Universal Design for Learning.

Dual Coding Theory

Paivio's Dual Coding Theory proposes that information can be processed through complementary cognitive systems involving verbal and non-verbal representations (Paivio, 1991). For deaf learners, simultaneous presentation of visual-nonverbal information through human sign language and visual-verbal information through printed AI captions provides complementary forms of representation.

In the present study, human sign language provided conceptual and linguistic information, while the AI-generated caption supplied a stable visual representation of the exact English orthography. The live text stream therefore functioned as a visual bridge connecting signed concepts with their written English forms (Paivio, 1991; Yoon and Kim, 2021).

Cognitive Load Theory

Cognitive Load Theory distinguishes among intrinsic load, extraneous load, and germane load. When DHH pupils attempt to decode rapid fingerspelling for unfamiliar academic vocabulary, the transient nature of the information may increase the demands placed on working memory. Real-time captions provide a relatively stable orthographic target that learners can visually reference while simultaneously attending to sign language.

The availability of a persistent textual representation may therefore reduce unnecessary cognitive demands associated with decoding transient fingerspelling and allow learners to devote greater cognitive resources to semantic processing and vocabulary development.

Universal Design for Learning

Universal Design for Learning advocates the provision of multiple means of representation, action and engagement to accommodate learner diversity. Integrating automated captioning establishes an additional means of representation through which DHH pupils can access instructional content. In this study, captioning complemented rather than replaced sign language interpretation, thereby supporting different levels of sign-language fluency, reading readiness and residual hearing.

Methodology

Research Design

The study adopted a quantitative quasi-experimental pretest-posttest control group design with a delayed posttest retention measure. A quasi-experimental design was considered appropriate because intact classroom settings were used to prevent ethical and administrative difficulties associated with disbanding established classes in a specialised school.

Participants were assigned through cluster randomisation at the level of intact instructional groups, rather than through individual random assignment. This distinction is important because the study retained the existing instructional structure of the school.

Research Design Layout

Table 1

Research Design Layout

Group	Pretest	Intervention	Immediate Posttest	Delayed Retention Test
Experimental Group (n = 15)	O ₁ (ELVA)	X ₁ (AI Captioning + Human Interpreter)	O ₂	O ₃
Control Group (n = 15)	O ₁ (ELVA)	X ₀ (Human Interpreter Only)	O ₂	O ₃

Participants and Setting

The target population comprised all Primary Five pupils enrolled at the Plateau State School for the Deaf, Bassa, Nigeria, during the 2025/2026 academic session. Primary Five was purposefully selected because it represents a crucial transitional academic stage in which pupils increasingly move from learning to read towards reading to learn in preparation for subsequent educational progression.

A total sample of thirty (N = 30) Primary Five DHH pupils participated in the study. The pupils were assigned through cluster randomisation into two intact instructional groups: Experimental Group (n = 15) and Control Group (n = 15).

Inclusion criteria required pupils to: (a) have severe-to-profound bilateral sensorineural hearing loss (≥ 71 dB HL); (b) rely on sign language as their primary classroom communication mode; and (c) have no co-occurring visual or intellectual disabilities.

Baseline Characteristics of Participants

Table 2

Baseline Demographic and Clinical Profile of Participants

Variable	Experimental Group (n = 15)	Control Group (n = 15)	Statistic / p-value
Age (Years, M $\pm$ SD)	11.87 $\pm$ 1.12	12.07 $\pm$ 1.03	t = 0.51, p = .614
Gender (Male / Female)	8 / 7	9 / 6	χ^2 = 0.13, p = .715
Hearing Loss Level (Severe / Profound)	4 / 11	5 / 10	χ^2 = 0.16, p = .691
Onset of Deafness (Pre-lingual / Post-lingual)	13 / 2	12 / 3	χ^2 = 0.24, p = .624

Variable	Experimental Group (n = 15)	Control Group (n = 15)	Statistic / p-value
Baseline Reading Level (Grade Equivalent)	2.1 ± 0.4	2.0 ± 0.5	t = 0.61, p = .547

The baseline results indicate that the two groups were comparable across the demographic and baseline characteristics reported in Table 2.

Technological and Instructional Setup

To address the specific infrastructural constraints of Plateau State, an offline, low-latency edge-computing setup was deployed in the Experimental Group classroom. The system hardware comprised an Intel NUC 12 edge-processing unit with a Core i7 processor and 32GB RAM running an optimised Whisper ASR model locally, requiring no active internet connection.

The classroom teacher wore an FM wireless lapel microphone (Sennheiser EW 112P G4) to capture a direct audio signal and reduce the effects of ambient classroom noise. Transcribed text was streamed in real time onto two 24-inch desk-mounted LED monitors situated adjacent to the certified human sign language interpreter at the front of the classroom. This arrangement allowed pupils to view the teacher, interpreter and text display within a relatively narrow visual field.

Intervention Procedure

The study lasted 14 weeks in total. This comprised one week for the pretest, eight weeks of instructional intervention, one week for the immediate posttest, and a four-week interval before administration of the delayed retention assessment. Both groups were taught identical English language modules derived from the official Nigerian Primary Five curriculum. Instruction focused on science vocabulary, comprehension passages, passive voice structures and specialised terminology. Instructional duration was standardised at 40 minutes per session, four days per week.

Experimental Group

Lessons delivered by the regular subject teacher were simultaneously interpreted into Nigerian Sign Language by a certified human interpreter and transcribed in real time onto student-facing displays using the offline AI engine. During instructional pauses, the teacher pointed to key technical terms displayed on the caption screen to reinforce connections among the spoken word, written form and signed concept.

Control Group

Lessons were delivered by the same subject teacher and interpreted into Nigerian Sign Language by a certified human interpreter using traditional instructional methods. No AI captioning or additional text-display technology was provided during instruction.

Instrument for Data Collection

Data were gathered using the English Literacy and Vocabulary Assessment (ELVA), a 40-item objective test developed by the researchers. The ELVA comprised three subscales:

1. Vocabulary Identification and Orthography — 15 items;
2. Contextual Word Meaning — 15 items; and
3. Passage Reading Comprehension — 10 items.

Total scores ranged from 0 to 100.

Validity and Reliability

Content validity of the ELVA was established through expert review by two professors of Special Education and one measurement expert. Formative pilot testing with an independent cohort of 12 DHH pupils produced a high internal consistency reliability coefficient ($KR-20 = 0.88$). Pretest assessments were administered one week before the intervention, posttests were conducted immediately following the eight-week intervention, and a delayed posttest was administered four weeks later to assess vocabulary retention.

Technical Data Collection

To evaluate technical feasibility, system logs automatically recorded Word Error Rate (WER) across the experimental instructional sessions. WER was calculated as:

$$\text{WER} = (\text{Substitutions} + \text{Deletions} + \text{Insertions}) / \text{Total Spoken Words} \times 100$$

Processing latency was also monitored by the system. However, because a verified numerical latency summary was not available in the supplied study results, no latency statistic has been introduced into the present article. Accordingly, Objective 3 is operationalised in the final article using WER as the reported technical accuracy measure.

Ethical Considerations

Ethical clearance was obtained from the Institutional Review Board of the Federal University of Education, Pankshin. Formal administrative approval was also granted by the Plateau State Ministry of Education and the Principal of Plateau State School for the Deaf, Bassa. Informed parental consent and pupil assent were secured for all participants. Following completion of the study, the Control Group was provided access to the AI captioning hardware to promote educational equity.

Results

Data were analysed using SPSS Version 28. Descriptive statistics, independent-samples t-tests, ANCOVA and paired t-tests were used as appropriate. Preliminary analyses included tests of normality using the Shapiro-Wilk test and homogeneity of variance using Levene's test.

Hypothesis 1

H01: There is no statistically significant difference in posttest English literacy and vocabulary scores between the Experimental Group and Control Group when controlling for pretest performance.

Table 3

Mean Literacy and Vocabulary Performance across Groups

Group	N	Pretest M (SD)	Posttest M (SD)	Mean Gain	Retention M (SD)
Experimental Group (AI + Sign)	15	41.20 (7.14)	74.20 (6.85)	+33.00	71.80 (7.10)
Control Group (Sign Only)	15	40.80 (6.92)	58.40 (7.92)	+17.60	52.60 (8.15)

As shown in Table 3, the Experimental Group recorded a higher posttest mean score ($M = 74.20$, $SD = 6.85$) than the Control Group ($M = 58.40$, $SD = 7.92$). An independent-samples t -test revealed a statistically significant difference between the groups, $t(28) = 5.84$, $p < 0.001$, Cohen's $d = 2.13$. The effect size was very large and favoured the Experimental Group.

To control for potential baseline variation, a one-way ANCOVA was conducted using pretest scores as the covariate. Preliminary checks confirmed equal regression slopes, $F(1, 26) = 0.12$, $p = 0.732$, and homogeneity of variance, $F(1, 28) = 0.38$, $p = 0.542$.

Table 4 ANCOVA Summary for Posttest Literacy Achievement, Controlling for Pretest

Source	Type III SS	df	Mean Square	F	p-value	Partial η^2
Pretest (Covariate)	182.41	1	182.41	3.31	.080	.109
Group (Intervention)	2128.53	1	2128.53	38.65	< .001	.589
Error	1486.26	27	55.05	—	—	—
Total	16742.00	30	—	—	—	—

As presented in Table 4, the main effect of the intervention was statistically significant, $F(1, 27) = 38.65$, $p < 0.001$, partial $\eta^2 = 0.589$. Consequently, H_01 was rejected.

Hypothesis 2

H02: There is no statistically significant difference in delayed posttest vocabulary retention scores between the Experimental Group and the Control Group.

The delayed retention results presented in Table 3 show that the Experimental Group obtained a mean retention score of 71.80 ($SD = 7.10$), whereas the Control Group obtained a mean retention score of 52.60 ($SD = 8.15$). An independent-samples t -test based on the reported group means and standard deviations indicated a statistically significant difference between the groups, approximately $t(28) = 6.88$, $p < 0.001$, Cohen's $d \approx 2.51$. The result favoured the Experimental Group. Consequently, H_02 was rejected.

The finding indicates that pupils who received AI-assisted real-time captioning alongside human sign language interpretation retained significantly more of the targeted vocabulary at the four-week delayed assessment than pupils who received human sign language interpretation alone.

The exact Hypothesis 2 test statistic should be verified against the original SPSS output before publication because the value reported here is calculated from the rounded means and standard deviations in Table 3.

Technical Performance

The technical evaluation recorded an average Word Error Rate of 8.4% across the experimental instructional sessions. This indicates that the locally deployed speech-recognition system achieved a relatively high level of transcription accuracy under the classroom conditions examined. Because no verified numerical processing-latency result was supplied in the original Results section, no latency statistic is reported here. Objective 3 therefore focuses on the documented WER result.

Discussion

The primary empirical finding of this study is that integrating AI-driven real-time captioning alongside human sign language interpretation produced statistically significant gains in English literacy and vocabulary acquisition among Primary Five DHH pupils in Plateau State. The Experimental Group outperformed the Control Group by 15.80 percentage points on the posttest assessment.

The finding supports the proposition underlying Paivio's Dual Coding Theory (Paivio, 1991). Pupils in the Experimental Group received simultaneous visual-nonverbal input through signing and visual-verbal input through captions. The combination may have provided complementary representations that strengthened the association between signed concepts and their written English forms.

The findings also align with Cognitive Load Theory. Rapid fingerspelling for unfamiliar academic vocabulary is transient and requires sustained visual attention. In contrast, real-time captions provide a stable orthographic representation that pupils can reference during instruction. The availability of this textual representation may reduce the cognitive demands associated with reconstructing the spelling of unfamiliar words from rapidly presented fingerspelling.

The retention result is particularly important. Four weeks after the immediate posttest, the Experimental Group retained a substantially higher mean vocabulary score than the Control Group. This suggests that the benefit of the intervention extended beyond immediate achievement. The simultaneous availability of signed concepts and written orthography may have provided repeated opportunities for learners to encode and retrieve new vocabulary.

The findings are also consistent with the importance of curriculum accessibility for deaf and hard-of-hearing learners (Stinson and Cawthon, 2015). Captioning should not be interpreted as a substitute for sign language. Rather, the findings suggest that text-based AI support can provide an additional access route to written English, particularly when pupils encounter unfamiliar or specialised vocabulary.

The technical finding is also significant. The average WER of 8.4% demonstrates that the locally deployed system was capable of producing relatively accurate captions under the conditions examined. This is relevant because caption accuracy is central to the educational usefulness of speech-to-text systems for deaf and hard-of-hearing learners (Matthew, 2020).

The deployment of edge computing was particularly relevant to the Nigerian context. Rather than depending continuously on cloud-based processing, the system processed speech locally, thereby reducing dependence on unstable internet connectivity. This demonstrates the importance of adapting AI-enabled assistive technologies to local infrastructural conditions.

Overall, the results support the use of AI captioning as a complementary orthographic scaffold, rather than as a replacement for human sign language interpretation. The human interpreter remains central to conceptual, linguistic and classroom communication, while AI captioning provides an additional visual representation of English speech.

Conclusion

This study demonstrates that AI-driven real-time captioning can function as an effective orthographic scaffold for enhancing English literacy, vocabulary acquisition and delayed vocabulary retention among Primary Five deaf learners in Nigeria.

When integrated collaboratively with human sign language interpretation, AI captioning provides a stable visual representation of English orthography while preserving the conceptual and linguistic contribution of sign language. The Experimental Group demonstrated significantly higher immediate posttest performance and significantly greater delayed vocabulary retention than the Control Group.

The technical evaluation produced an average Word Error Rate of 8.4% under the classroom conditions examined. The use of offline edge-computing architecture also provides a potentially practical approach to deploying AI-assisted educational technologies in Nigerian special-school environments affected by unreliable internet connectivity.

Recommendations

Based on the findings of the study, the following recommendations are made:

1. Institutional Adoption of Dual Scaffolding: State Ministries of Education and administrators of special schools should consider adopting AI real-time captioning as an

auxiliary instructional technology that complements, rather than replaces, qualified human sign language interpreters.

2. Deployment of Edge-Computing Hardware: Educational technology procurement for special schools should prioritise offline or edge-processing hardware and appropriate microphones capable of improving speech capture in noisy classroom environments.
3. Teacher Capacity Building: Professional development programmes should equip special education teachers with the skills required to use AI captioning effectively, including appropriate speech pacing, clear enunciation, management of specialised vocabulary and integration of captions with sign-supported instruction.
4. Expansion of Empirical Research: Future research should replicate the intervention using larger samples across multiple states and educational levels in Nigeria. Further studies should also investigate AI captioning in other subject areas, including Mathematics, Science, Technology, Engineering and Mathematics (STEM), as well as examine long-term literacy outcomes.

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