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Mitigating Cognitive Overload in Deaf Education: The Pedagogical Impact of a Multimodal Instructional Design on Digital Media Literacy Retention

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Abstract. In evolving digital landscapes, the acquisition of digital media literacy (DML) remains a systemic challenge for deaf and hard-of-hearing (DHH) students. This disparity is largely driven by the extraneous cognitive overload and the split-attention effect caused by conventional, auditory-centric multimedia designs relegating sign language and captions to peripheral windows. This study investigates the educational efficacy of a newly developed multimodal instructional framework engineered to address these barriers by integrating a prominent visual-spatial sign language interface (Big Sign) with Universal Design for Learning (UDL) principles. Employing a one-group quasi-experimental approach, the research evaluated the proposed framework by comparing baseline pre-test scores against immediate knowledge acquisition and short-term retention among 30 DHH learners in higher education over a two-week period. Statistical analyses revealed that the intervention significantly improved initial DML competency (pre-test to post-test) and sustained high retention rates over two weeks. Furthermore, qualitative assessments conducted via semi-structured interviews highlighted a transition from fragmented, visually taxing attention patterns to a more integrated and naturalistic visual learning experience, thereby maximizing pedagogical engagement. While limited by the absence of a control group, these findings offer a scalable, evidence-based model for educators and instructional designers to transcend mere technical accessibility compliance and move toward the creation of cognitively equitable digital learning environments that optimize knowledge encoding for DHH populations.

Keywords: cognitive load theory; deaf education; digital media literacy; multimodal instruction; universal design for learning

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1. Introduction

In contemporary educational landscapes, navigating digital environments is a fundamental requirement for student autonomy, social equity, and academic success. It is critical, however, to distinguish the nuances within this domain: while digital literacy generally focuses on the operational skills required to use technology and media literacy emphasizes the critical analysis of content, digital media literacy (DML) serves as a synthesis of the two (Bulger & Davison, 2018; Spires et al., 2019; UNESCO Institute for Statistics, 2018). DML requires users to operationally navigate platforms while critically evaluating, curating, and safely applying digital information within complex ecosystems. As educational institutions transition toward technology-mediated environments, the ability to apply DML is paramount (Livingstone, 2022; Qing & Jing, 2024; Tabieh et al., 2021; Valle et al., 2025).

However, this rapid and often uncoordinated digital transformation has inadvertently widened the educational divide, creating a new gap that transcends simple hardware ownership. Instructional media designs frequently default to hearing-centric standards, designed by and for the hearing majority, thereby failing to accommodate the diverse cognitive processing needs of learners with disabilities, a challenge that persists globally within higher education web environments (Campoverde-Molina et al., 2023).

Most digital tools and platforms are built on the assumption that audio-visual information are mutually supplementary, rather than considering how the lack of one channel affects the processing of the other. Consequently, the contemporary digital divide is no longer merely an issue of technological access or having a device, but rather a profound disparity in cognitive accessibility and pedagogical equity (Cho & Kim, 2022; Sachdeva et al., 2015). When the architecture of learning is inherently biased toward a specific sensory modality, it effectively disenfranchises those who rely on alternative pathways for information acquisition, turning digital tools into barriers rather than bridges.

For deaf and hard-of-hearing (DHH) students, standard digital learning environments often impose an extraneous cognitive burden that severely hinders information processing and knowledge construction (Krasavina et al., 2025; Venkatesan, 2025). While a hearing student might effortlessly absorb a lecture through simultaneous listening and watching, a DHH student must engage in a much more taxing mental exercise to achieve the same level of understanding.

Traditional pedagogical media rely heavily on auditory channels, supplemented only post-production by standard captions or diminutive sign language interpreter windows, which are often treated as add-ons rather than core components of the design (Alsalamah, 2020). This conventional layout forces DHH learners into a continuous state of split attention (Blom et al., 2019; DeForte et al., 2020) wherein the brain is forced to process two or more competing sources of visual information that are physically separated on the screen, such as a PowerPoint slide and a small sign language video in the corner.

Students must rapidly and constantly shift their gaze between the primary instructional content, the textual subtitles, and the interpreter, leading to rapid visual fatigue and mental exhaustion. This constant eye movement is not merely a physical inconvenience; it represents a significant interruption in the flow of information. Viewed through the lens of cognitive load theory, this constant visual shifting depletes the learner's finite working memory capacity, which is already working at high intensity to decode sign language or read captions in real-time.

When the working memory is saturated by the noise of navigating a poorly designed interface, insufficient cognitive resources remain for the actual comprehension, critical analysis, and deep encoding of the complex DML concepts being presented (Krasavina et al., 2023). Without the ability to chunk information or relate new data to existing knowledge, the DHH learner is often left with fragmented understanding, significantly lagging behind their hearing peers in the mastery of digital literacy.

While global policy frameworks increasingly advocate for inclusive education and universal access, mere technical compliance, such as adding basic subtitles to satisfy legal accessibility mandates or providing a transcript, does not guarantee pedagogical effectiveness or true learning mastery (Burke et al., 2016; King & Piotrowski, 2021). Compliance is often a check-the-box activity that satisfies the law but ignores the actual lived experience of the student. True educational inclusion requires a paradigm shift from retrofitted accommodations, trying to fix a broken design after it is built, to proactive instructional design that considers diversity from the outset. To foster deep, retainable DML skills that students can apply in real-world scenarios, educational interventions must align with the visual-spatial processing strengths inherent in Deaf culture, a concept increasingly recognized as Deaf Aesthetics (Skyer, 2023; Weber et al., 2025).

This pedagogical approach posits that instructional materials should centralize visual learning modalities rather than treating them as peripheral aids or secondary help features. Deaf Aesthetics in education means designing interfaces where the sign language interpreter is large enough to show facial grammar (which is essential for meaning) and where text and graphics are synchronized in a way that minimizes eye travel. By capitalizing on spatial awareness and visual synchronicity, educators can transform a cognitively exhausting task into a natural, integrated learning experience. Instead of fighting against the medium, the learner can use their natural visual-spatial talents to grasp complex concepts, such as identifying phishing emails or understanding data encryption, with the same ease as a hearing person listening to an explanation.

Despite the critical need for such specialized environments, there remains, however, a notable scarcity of empirical research evaluating the long-term efficacy of visually optimized instructional formats, particularly concerning the retention of complex literacy skills among DHH populations (Alsalamah, 2020; Rutledge, 2025). Much of the existing literature focuses on immediate satisfaction or basic accessibility access rather than the higher-order cognitive gains over time.

Consequently, this study seeks to bridge these specific instructional gaps by systematically designing, developing, and empirically testing a customized multimodal learning format specifically tailored for DHH higher education students. Crucially, this research addresses a multi-dimensional empirical gap by providing quasi-experimental evidence on the short-term retention of complex digital media literacy (DML) topics among DHH populations using visually optimized instructional formats.

By grounding the intervention in cognitive load theory and Universal Design for Learning (UDL) principles (AlRawi & AlKahtani, 2021; Evmenova et al., 2024), this research introduces a prominent visual-spatial interface, featuring an oversized sign language display paired with enhanced, synchronized textual support and high-contrast visual cues. This design explicitly aims to reduce extraneous cognitive load by bringing together the necessary information sources into a single, cohesive visual field. Ultimately, this investigation aims to redefine how digital literacy is taught to DHH students, shifting the academic focus from basic informational access, which is the bare minimum, to the optimization of cognitive processing and the maximization of long-term knowledge retention. By doing so, we move closer to a truly equitable digital future where the medium of instruction no longer limits the potential of the learner.

2. Literature Review

2.1 Cognitive Processing and Multimedia Learning in DHH Education

The conceptual foundation of this investigation is anchored in dual-coding theory (Paivio, 1986, 1991) and cognitive load theory (Sweller, 1988, 1994). It is critical, however, to distinguish their mechanisms within this context: while cognitive load theory emphasizes the need to minimize extraneous distractions to prevent working memory overload, dual-coding theory highlights the capacity to enhance learning by simultaneously engaging independent visual and verbal processing channels (Mayer, 2014), asserting that learning is optimized when extraneous processing is minimized within complex digital environments (Davis, 2020; Muchuweni & Jojo, 2026). This is particularly vital in deaf education.

Foundational research on cognitive processing in DHH individuals (Marschark et al., 2008) highlights that visual attention and working memory operate differently when relying entirely on visual pathways. Traditional instructional media often fail to harmonize these mechanisms, presenting text and standard, diminutive sign language displays in a manner that forces DHH students to divide their visual attention (Blom et al., 2019; DeForte et al., 2020; Krasavina et al., 2023), precipitating a detrimental split-attention effect. By integrating an oversized visual-spatial interface, this pedagogical design hypothesizes a substantial reduction in extraneous cognitive burden, thereby optimizing the learner's working memory ability to encode and internalize digital media literacy concepts effectively (Gareyev et al., 2023; Krasavina et al., 2023).

2.2 Digital Media Literacy and Accessible Design

Navigating the digital landscape is no longer a peripheral skillset; it is a critical educational prerequisite for social equity and civic participation, necessitating a shift toward computational thinking and specialized literacy frameworks for DHH learners (Kritzer & Smith, 2020). Comprehensive educational frameworks emphasize the necessity of developing competencies across information evaluation, safe communication, and problem-solving (UNESCO Institute for Statistics, 2018; Valle et al., 2025). For instructional interventions to be truly efficacious for marginalized learners, however, they must facilitate a transition from abstract theoretical comprehension to concrete behavioral adaptation (Ibraimkulov et al., 2022), empowering students to navigate complex digital environments securely and autonomously (Livingstone, 2022), while ensuring equity in all instructional activities (Graham et al., 2023).

Furthermore, standard compliance mechanisms often fail to deliver pedagogical equity. Frameworks established by institutions such as the Rochester Institute of Technology (RIT) or the National Technical Institute for the Deaf (NTID) emphasize the necessity of accessible design that goes beyond post-production captions. Integrating Deaf Aesthetics leverages the inherent visual-spatial strengths of DHH individuals to foster deeper engagement.

2.3 Pedagogical Inclusion through Universal Design and Visual Aesthetics

While educational policies frequently mandate accessible learning materials, standard compliance mechanisms often fail to deliver genuine pedagogical equity. Universal Design for Learning (UDL) dictates that instructional environments must be proactively engineered from the outset to eliminate learning barriers (AlRawi & AlKahtani, 2021; Evmenova et al., 2024; Rutledge, 2025). Conventional captioning, for instance, frequently suffers from temporal desynchronization, which can severely hinder knowledge acquisition for DHH students. Emerging educational paradigms advocate for Deaf Aesthetics, leveraging the inherent visual-spatial strengths of DHH individuals (Alit et al., 2025; Boyle et al., 2024; Fernández et al., 2022). This study explores how integrating these visual paradigms, specifically through prominent multimodal layouts, can foster deeper educational engagement.

2.4 Instructional Barriers and Literature Gaps

While educational technology continues to advance, a disparity persists regarding higher-order digital literacy among DHH populations. Although DHH students frequently master basic operational skills, they often encounter challenges with critical literacy and complex digital navigation (Abdullina & Zolotovitskaya, 2023; Cabero et al., 2023; Krasavina et al., 2025; Venkatesan, 2025). The shift toward virtual learning environments has further highlighted the need for specialized instructional strategies to support pedagogical equity and effective online collaboration (Graham et al., 2023).

Furthermore, existing literature primarily addresses technical accessibility rather than evaluating the pedagogical efficacy of multimodal formats designed to foster higher-order critical thinking (Alsalamah, 2020; Rutledge, 2025). Notably, there is limited quasi-experimental evidence examining the short-term retention of knowledge following instructional interventions within this demographic, which restricts broader efforts to improve digital literacy among students with diverse disabilities (Ibraimkulov et al., 2022). To address this gap, the current study investigates how a cognitively optimized instructional design can support sustained knowledge retention.

2.5 Research Objectives and Questions

To address the identified pedagogical and empirical gaps within the existing literature, this study proposes a cognitively optimized multimodal instructional design. The overarching objective is to close the digital literacy divide for DHH learners by mitigating cognitive overload. Specifically, this investigation is guided by three consolidated research questions:

a. RQ1: What are the essential pedagogical components required to design a multimodal learning environment that authenticates Deaf Aesthetics, and how do experts evaluate its quality?
b. RQ2: To what extent does the multimodal instructional intervention improve immediate digital media literacy (DML) acquisition and sustain short-term knowledge retention?
c. RQ3: How do DHH learners articulate the impact of the visual-spatial interface on their cognitive load, and how do they practically apply the acquired DML verification skills?

2.6 Conceptual Framework

To synthesize the theoretical foundations into a testable pedagogical model, this study employs an Input-Process-Output (IPO) conceptual framework. Figure 1 illustrates the hypothesized relationships between the multimodal instructional design, the learners' cognitive processing, and the ultimate educational outcomes.

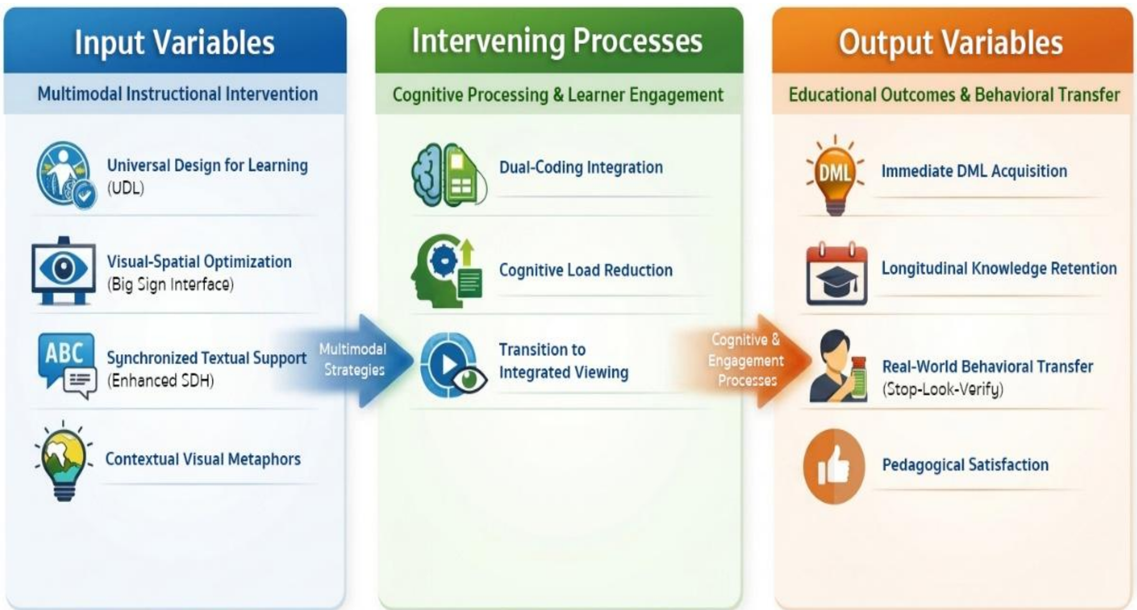

Figure 1: The Pedagogical Impact of Multimodal Instructional Design on Cognitive Processing and DML Retention among DHH Learners

As depicted in Figure 1, the framework delineates the educational intervention into three interconnected phases. The Input represents the multimodal instructional intervention itself, which integrates Universal Design for Learning

(UDL) principles, an enlarged visual-spatial interface (Big Sign), and synchronized enhanced captions (SDH). This carefully engineered learning environment is hypothesized to trigger specific cognitive mechanisms during the Process phase. By reducing extraneous cognitive load and mitigating split-attention effects, the design optimizes working memory, allowing DHH learners to achieve dual-coding integration and experience seamless integrated viewing. Ultimately, these optimized cognitive processes are expected to yield the targeted educational Outputs. These encompass immediate digital media literacy acquisition, short-term knowledge retention, high pedagogical satisfaction, and the behavioral transfer of critical verification skills (e.g., the Stop-Look-Verify heuristic) into real-world digital contexts.

To ensure methodological repeatability, each component of this framework was strictly operationalized. The Input design elements were evaluated using the expert pedagogical evaluation rubric. The Process variables (cognitive load reduction and integrated viewing) were assessed qualitatively via the semi-structured interview protocol and, finally, the Output variables (knowledge acquisition and retention) were quantified utilizing the standardized DML assessments and analyzed via paired-samples t-tests, while pedagogical satisfaction was measured using a 5-point Likert scale inventory.

3. Methodology

3.1 Research Design

This investigation employed a rigorous design and development research (DDR) framework, systematically progressing through pedagogical analysis, multimodal design, AI-integrated development, and empirical evaluation phases. This approach was integrated with a one-group pre-test-post-test-retention test quasi-experimental design (DeForte et al., 2020; Krasavina et al., 2023). While the absence of a control group limits strict causal interpretation and cannot completely rule out natural maturation or testing effects, this design was necessitated by the logistical challenges of recruiting a sufficiently large and accessible cohort of DHH learners for dual-group comparison.

3.2 Participants

The study involved two distinct groups selected through purposive sampling from higher education students in Udon Thani Province. The first group comprised a panel of educational technology and accessibility specialists ($N = 9$) selected based on their expertise in special education and multimedia design. The primary experimental cohort consisted of Deaf and Hard-of-Hearing (DHH) undergraduate students ($N = 30$; Age range = 18–22 years; 16 males, 14 females).

Inclusion criteria required participants to have severe-to-profound hearing loss, utilize Thai Sign Language (TSL) as their primary mode of communication, and have no prior formal training in advanced digital media literacy. To justify this sample size, a post-hoc power analysis was conducted using G*Power, indicating that $N = 30$ provided sufficient statistical power ($1 - \beta > 0.95$) to detect large effect sizes. To explore cognitive impacts qualitatively, maximum variation sampling was subsequently utilized to select a subset of 10 students for in-depth interviews.

3.3 Research Instruments

Data collection was facilitated through three primary, self-developed instruments, rigorously validated prior to deployment:

1. Pedagogical Evaluation Rubric: A 5-point Likert scale assessing three dimensions (Content Quality, Design/Production, and Visual Accessibility). It achieved a high content validity index (CVI = 0.92) following expert review.
2. Digital Media Literacy (DML) Assessment: A standardized 20-item multiple-choice test (score range: 0–20) adapted from established UNESCO digital literacy frameworks, covering domains such as identifying misinformation and data privacy. The language was visually scaffolded to match DHH reading levels. It demonstrated strong internal consistency (Cronbach's alpha = 0.84).
3. Semi-Structured Interview Guide: Formulated to elicit qualitative insights regarding visual fatigue and real-world DML application. The protocol was theoretically grounded in cognitive load theory, validated by experts (Index of Item Objective Congruence [IOC] = 0.88), and translated into TSL by certified interpreters to ensure cultural appropriateness.

3.4 Research Procedures

The study was systematically executed across four developmental and evaluative phases:

a. Phase 1: Needs Assessment and Prototyping: Focus group discussions established the visual-spatial prerequisites of DHH learners, guiding the initial development of the Big Sign and enhanced SDH multimodal interface.
b. Phase 2: Formative Evaluation: The expert panel systematically appraised the prototype, followed by a pilot test to rectify technical and cognitive barriers.
c. Phase 3: Efficacy Assessment: The N = 30 cohort underwent the main quasi-experimental intervention. To ensure methodological consistency, all students were exposed to the exact same standardized instructional sequence. The intervention consisted of four 45-minute multimedia modules covering core DML topics (e.g., fake news identification, phishing, and digital footprints) delivered via a controlled learning management system (LMS). During the intervention, the AI-Presenter delivered the primary content while the AI-Sign Language interface provided synchronized visual translation. DML learning outcomes were quantified immediately and two weeks post-intervention.
d. Phase 4: Qualitative Exploration: Sign-language-mediated interviews were conducted to deeply understand the learners' transition to integrated viewing and behavioral skill transfer.

Regarding the instructional media development, a localized deep-learning AI sign language synthesis system was utilized. To ensure linguistic accuracy and cultural appropriateness, the AI's output, particularly its non-manual markers (facial expressions), was rigorously validated by a panel of three native Deaf signers and certified interpreters prior to the intervention. This technological integration directly embodies Deaf Aesthetics by allowing for the Big Sign visual-spatial interface, optimizing legibility and honoring the community's visual-centric communication norms.

3.5 Data Analysis and Qualitative Rigor

Quantitative data derived from the expert evaluations and DML assessments were analyzed using descriptive statistics (M and SD). Prior to inferential testing, data distributions were examined and met the assumptions of normality. To evaluate longitudinal knowledge retention, paired-samples t-tests were employed with the alpha level set a priori at .05. Complete statistical outputs, including exact p-values, degrees of freedom (df), 95% confidence intervals (CIs), and Cohen's d effect sizes, were calculated to determine practical significance.

There were no missing data in the final dataset. Conversely, qualitative data from the semi-structured interviews underwent rigorous thematic analysis. Interviews were transcribed, and a systematic coding procedure was employed by two independent coders. An initial codebook was developed deductively from cognitive load theory and inductively from participant responses. The coders established strong inter-rater reliability (Cohen's Kappa = 0.85). Credibility was further ensured through rigorous member-checking procedures with the participants.

4. Results

4.1 Pedagogical Needs Assessment for DHH Learners

Initial evaluations highlighted a critical demand for specialized instructional formats. Data were collected using an identical 5-point Likert scale (1 = Lowest Need, 5 = Highest Need) from two distinct participant groups: DHH undergraduate students (n = 30; M = 4.53) and educational stakeholders comprising special education experts and instructional designers (n = 9; M = 4.63). The qualitative consensus established three non-negotiable pedagogical components: a prominently enlarged sign language interface (Big Sign) to reduce visual strain, synchronized enhanced text (SDH), and the strategic use of visual metaphors to clarify abstract digital literacy concepts.

Table 1: Pedagogical Needs Assessment Results for DHH Instructional Media

Category	Identified Pedagogical Requirement	Mean (*M*)	Interpretation
Instructional Content	Practical guidelines tailored specifically for the DHH community	4.53	Highest
Technological Interface	Integration of prominent visual symbols (Big Sign, Enhanced SDH)	4.63	Highest
	Overall Average	**4.58**	**Highest**

Note. N = 30. M = Mean. Scores reflect the highest level of need evaluated by stakeholders on a 5-point Likert scale (1 = Lowest Need, 5 = Highest Need).

4.2 Expert Validation of the Instructional Design

The developed educational intervention, crafted through a collaborative five-step methodology, integrated advanced assistive media features. A panel of nine educational and accessibility experts awarded the instructional package the highest quality rating (M = 4.73, SD = 0.51). The targeted visual-spatial accommodations received exceptional evaluations, particularly the oversized sign language interface (M = 5.00) and the integration of an AI-driven presenter (M = 4.86), confirming the technical and pedagogical robustness of the design.

Table 2: Quality Evaluation Results of DML Streaming Programs for DHH Learners

Evaluation Criteria	Mean (*M*)	*SD*	Interpretation
Content Quality	4.81	0.40	Highest
Design and Production Quality	4.67	0.57	Highest
Visual and Technological Accessibility	4.71	0.56	Highest
Overall Average	**4.73**	**0.51**	**Highest**

Note. N = 9. M = Mean. Scores reflect the highest level of quality evaluated by experts on a 5-point Likert scale (1 = Lowest Quality, 5 = Highest Quality)

Qualitative thematic analysis revealed that the experts found the program highly engaging, particularly through its innovative integration of artificial intelligence (AI) to enhance media production. Key features highlighted included the AI-driven Sign Language Interpreter (AI-Sign Language) and AI-Presenters. The experts also emphasized that the program significantly improved communication clarity for DHH viewers by utilizing a prominent visual-spatial interface, specifically the Big Sign (oversized sign language display) and Automatic Closed Captioning (Auto-CC). These specialized digital streaming characteristics were identified as highly beneficial and essential features tailored to the specific needs of the target audience.

Figure 2: Components of the Multimodal Instructional Environment

4.3 Efficacy of Learning Outcomes and Knowledge Retention

The quasi-experimental evaluation (N=30) measured DML acquisition. A paired-samples t-test indicated a significant increase in knowledge from the pre-test (M = 6.40, SD = 1.35) to the immediate post-test (M = 11.60, SD = 1.20); $t(29) = 15.42$, $p < .001$, 95% CI [4.51, 5.89], Cohen's $d = 2.81$. In practical terms, this demonstrates that the students nearly doubled their capacity to identify, evaluate, and safely interact with digital media after using the multimodal framework. Furthermore, the two-week retention assessment yielded a slight increase (*M* = 11.90, *SD* = 1.56). The difference between the post-test and retention test was not statistically significant, ($t(29) = 1.25$, $p = .221$, 95% CI [-0.19, 0.79], $d = 0.22$, indicating that the knowledge was successfully sustained. The marginal increase of 0.30 during the retention phase likely reflects minor testing effects (practice on similar items) or continued participant reflection post-intervention. For educators, this confirms that reducing visual barriers not only aids immediate understanding but also enables DHH learners to securely store this complex literacy information in their long-term memory.

Table 3: Short-term Analysis of DML Knowledge Retention (Pre-test, Post-test, and 2-Week Follow-up)

Assessment Phase	Mean (*M*)	*SD*	*t*	*p*	*d*	Result
Pre-test	6.40	1.35	-	-	-	Baseline
Immediate Post-test	11.60	1.20	15.42	< .001	2.81	Significant Gain
2-Week Follow-up	11.90	1.56	1.25	.221	0.22	Knowledge Retained

Note. N = 30. The t-statistic and Cohen's d for the Immediate Post-test represent the comparison with the baseline Pre-test. The statistical values for the 2-Week Retention represent the comparison with the Immediate Post-test.

4.4 Learner Satisfaction and Engagement

Post-intervention assessments revealed that the DHH student cohort experienced the highest level of overall satisfaction (M = 4.70, SD = 0.53) with the tailored learning environment. Specifically, the itemized analysis highlighted that key visual-spatial features achieved exceptionally high ratings; the oversized sign language interface (Big Sign) obtained the highest satisfaction score (M = 4.87, SD = 0.35), closely followed by the synchronized enhanced captions (M = 4.80, SD = 0.41). These findings underscore the framework's success in meeting the unique cognitive and cultural requirements of DHH learners.

Table 4: Learner Satisfaction with Multimodal Instructional Features

Evaluation Items	Mean (*M*)	*SD*	Interpretation
1. Content is engaging and interesting	4.67	0.47	Highest
2. Content is easy to understand and appropriate for the format	4.73	0.45	Highest
3. AI-Sign Language (AI-SL) integration is appropriate	4.70	0.60	Highest
4. Auto-Closed Captions (Auto-CC & SDH) are appropriate	4.80	0.41	Highest
5. Illustrations and graphics are appropriate	4.67	0.55	Highest
6. Video elements are congruent with the content	4.63	0.61	Highest
7. Font size is clear and appropriately scaled	4.57	0.73	Highest

8. Oversized sign language interface (Big Sign) is highly visible and appropriately sized	4.87	0.35	Highest
9. Media interface is user-friendly and easy to view	4.60	0.67	Highest
10. AI-Presenter integration is appropriate	4.77	0.50	Highest
Overall Satisfaction	**4.70**	**0.53**	**Highest**

Note. N = 30. Satisfaction was evaluated on a 5-point Likert scale (1 = Lowest Satisfaction, 5 = Highest Satisfaction).

4.5 Qualitative Insights on Cognitive Load and Skill Transfer

Thematic analysis revealed profound shifts in cognitive processing. Participants consistently reported mitigated visual fatigue, allowing a transition to integrated viewing. Instead of struggling to divide their attention between a tiny interpreter window and the main lesson, a process that quickly drains mental energy, students could comfortably process the educational information and the AI-generated sign language as a unified whole. Furthermore, the students demonstrated functional behavioral transfer, actively applying the learned Stop-Look-Verify heuristic to successfully identify authentic digital threats, such as phishing attempts and fabricated news within sports media contexts, in their daily routines.

To guarantee the authenticity and empirical rigor of these qualitative findings, all semi-structured interviews were conducted utilizing Thai Sign Language (TSL). The responses were subsequently translated into written text by certified sign language interpreters, and the accuracy of the transcribed quotes was rigorously verified through member checking with the participants to ensure communicative validation.

Table 5: Thematic Analysis of Cognitive and Behavioral Outcomes in DHH Learners

Theme	**Prevalence (n/30)**	**Illustrative Quote (Translated from Sign Language)**
Reduced Visual Fatigue	26/30	"I experienced no visual fatigue when watching the interpreter; the whole process felt seamless."
DML Application	24/30	"Upon noticing a sports news and deceptive financial post on social media, I actively applied verification strategies and confirmed it was a scam."

Note. DML = Digital Media Literacy. Participant quotes were originally expressed in Thai Sign Language (TSL), translated into written text by certified sign language interpreters, and rigorously verified for accuracy through member checking with the participants.

5. Discussion

5.1 The Efficacy of Participatory Instructional Design

The exceptional expert evaluations (*M* = 4.73) validate the implementation of a rigorous, community-driven development framework. By actively integrating DHH learners into the foundational design phases, the resulting educational tool achieved both linguistic precision and technological resilience. This paradigm shift highlights the necessity of evolving Universal Design for Learning (UDL) from a static compliance checklist into a dynamic, learner-centric pedagogical strategy that directly addresses accessibility shortcomings, particularly in defining the criteria and methods needed to evaluate digital competencies in specialized learning environments (Gareyev et al., 2023).

5.2 Mitigating Cognitive Overload through Dual-Coding

A central revelation of this study is the remarkable stability of the learners' acquired knowledge, evidenced by the lack of significant score degradation over a two-week period ($p > .05$). While recognizing the absence of a comparison group, this empirical finding provides preliminary evidence supporting the application of cognitive load theory and dual-coding theory in inclusive education. While conventional, auditory-focused media exhaust the working memory of DHH students on basic comprehension, the intentional combination of an oversized visual interface and synchronized text optimally leveraged multiple encoding channels to solidify learning. This stability is crucial, especially considering how external disruptions or shifts in learning environments can significantly impact the long-term reading and learning trajectories of DHH students (Kuntze et al., 2023).

5.3 Achieving Cognitive Synchronicity in Visual Learning

Qualitative feedback strongly illuminates the cognitive mechanics behind the format's success. Traditional instructional layouts inadvertently generate a split-attention effect, demanding constant visual oscillation between the primary educational content and the translation. By embracing Deaf Aesthetics and centralizing the sign language interpreter as a primary focal point, the cognitive effort required for visual scanning was drastically minimized. This spatial reorganization supported a transition from a highly taxing cognitive task into a fluid, cohesive learning experience, mirroring findings that emphasize the need to optimize media formats specifically for the cognitive and visual processing profiles of DHH learners (Kuntze et al., 2023).

5.4 Translating Theoretical Literacy into Digital Resilience

Ultimately, the true metric of digital media literacy is its translation into protective behavioral habits. Post-study interviews confirmed that students internalized and independently deployed the Stop-Look-Verify methodology to navigate real-world digital hazards, such as deceptive SMS links and misinformation. By embedding critical literacy instruction within engaging, contextually relevant media like sports broadcasting, this instructional model empowers DHH individuals to participate in the digital ecosystem with the same critical autonomy and skepticism as their hearing counterparts.

5.5 Limitations of the Study

While this study provides valuable insights, several limitations must be acknowledged. First, the single-group quasi-experimental design lacks a randomized control group, limiting the ability to make definitive causal claims and rule out external testing effects. Second, the purposive sample size ($N = 30$) is relatively small; although a post-hoc power analysis indicated sufficient statistical power to detect large effects, caution is required regarding broad generalizability. Third, the two-week retention window primarily captures short-term memory consolidation rather than long-lasting longitudinal learning. Fourth, the reliance on an AI-generated sign language interpreter introduces boundary conditions regarding nuanced human expressions. Finally, cognitive load was evaluated indirectly through qualitative self-reports of visual fatigue rather than via validated psychometric instruments (e.g., NASA-TLX). Future research should employ true experimental designs with larger cohorts and standardized cognitive load metrics over extended periods.

6. Conclusion

This research successfully conceptualized, developed, and empirically evaluated a multimodal instructional framework tailored to the cognitive architectures of Deaf and Hard-of-Hearing (DHH) learners. By prioritizing pedagogical components such as a prominent visual-spatial interface (Big Sign), synchronized enhanced text (SDH), and contextual visual aids, the study established a new paradigm for digital media literacy (DML) education. The rigorous participatory design process yielded an educational intervention of exceptional instructional quality.

Crucially, the quasi-experimental evaluation demonstrated that this cognitively optimized format is positively associated with robust, short-term knowledge retention, with learners exhibiting no significant memory decay over a two-week period. This indicates that the strategic multimodal layout appeared to minimize extraneous cognitive load, thereby supporting memory encoding. Qualitative evidence further illuminated that this pedagogical approach successfully mitigated the split-attention effect, allowing learners to engage in seamless integrated viewing without visual fatigue.

Ultimately, the intervention achieved its paramount educational objective: translating classroom literacy into functional, real-world behavioral resilience, as evidenced by students' sustained application of critical verification strategies in their daily digital interactions. This model offers a promising, adaptable framework for inclusive digital education. By centering instructional design around Deaf Aesthetics, educators can transform traditional media into powerful cognitive tools that empower marginalized learners to navigate the digital economy critically and autonomously.

7. Educational and Policy Implications

7.1 Theoretical Contributions to Educational Psychology

This investigation provides robust empirical validation for integrating Universal Design for Learning (UDL) with cognitive load theory (CLT) in special education contexts. It demonstrates that the debilitating split-attention effect, prevalent in traditional multimedia learning, can be systematically mitigated through deliberate spatial optimization, such as the prominent visual interface. Furthermore, the success of the participatory development model underscores the critical importance of incorporating Deaf Aesthetics into instructional design. It proves that genuine educational inclusion requires aligning visual-spatial hierarchies with the specific cognitive processing modalities of DHH individuals, rather than merely providing superficial linguistic translations.

7.2 Practical Recommendations for Instructional Design and Policy

Drawing directly from the empirical evidence of this study, educators and instructional technologists should adopt prominent sign language interfaces (Big Sign) and synchronized textual supports as foundational pedagogical standards to fundamentally enhance cognitive comprehension. On a broader normative level, educational institutions and regulatory bodies should transition away from inadequate corner-box translation models by mandating high-visibility instructional standards in all digital learning policies.

Furthermore, while AI-mediated sign-language features offer a highly scalable and cost-effective solution for inclusive media production, they present inherent accessibility risks, particularly regarding the accuracy of nuanced non-manual markers and facial grammar. Therefore, institutional policies must mandate human interpreter oversight to validate AI outputs, ensuring that technological scalability does not compromise linguistic authenticity or Deaf cultural nuances. Finally, integrating critical digital safety training within engaging, culturally relevant multimedia formats, such as inclusive sports broadcasting, should be prioritized to safeguard vulnerable learners within the broader digital landscape.

Conflict of Interest

The authors declare no conflicts of interest with respect to the research, authorship, and/or publication of this article.

8. Generative AI Tools Declaration

Gemini (Google, 2026) and Grammarly (Grammarly Inc., 2026) were used to refine the language and grammar of the manuscript. Notwithstanding the use of these tools, the paper remains an authentic representation of the authors' research and intellectual contributions. The authors performed all research design, data analysis, and interpretations.

9. Ethical Statement

Ethical approval for this study was granted by the Institutional Review Board (IRB) of Mahasarakham University. All participants provided informed consent prior to engagement, and strict measures were implemented to guarantee data protection and participant confidentiality throughout the research process. Furthermore, comprehensive accessibility accommodations, including the provision of certified Thai Sign Language (TSL) interpreters, were ensured during all phases of data collection. Due to privacy and ethical restrictions regarding this vulnerable demographic, the datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

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