Developing an Immersive Learning Environment for Visual Sign Language Acquisition on Specific Vocabulary in Print Design: Toward Equitable Education for Deaf Learners

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***Abstract*—This research presents the design and development of an immersive learning environment aimed at facilitating visual sign language acquisition for Deaf and Hard of Hearing (DHH) learners in the context of domain-specific vocabulary within print design. Grounded in a hybrid instructional design approach that integrates the systematic structure of the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) model with the learner-centered principles of Design Thinking, the platform was implemented via Spatial.io to deliver a multimodal, self-paced, and visually rich learning experience aligned with the cognitive strengths of DHH learners. The environment comprises four pedagogically structured zones: the Inspire Zone for project introduction and community motivation, the QuickSign Zone for flashcard-based drills with pre- and post-tests, the DeepSign Lab for looped video demonstrations of sign vocabulary, and the Gallery Zone for reflection and peer project display. Instructional materials were delivered through animated flashcards, Quick Response (QR)-linked sign language videos, and embedded formative assessments, supporting individualized interaction and asynchronous learning. Preliminary evaluation results indicate high usability and learner engagement, highlighting the platform' s strong potential to promote equitable access to professional knowledge in design education and to address the ongoing shortage of specialized sign language learning resources in technical and creative fields.**

***Keywords*—immersive learning environment, sign language, deaf learners, print design, instructional design**

I. Introduction

Sign language is a fully developed natural language with its own grammar, lexicon, and spatial-visual structure, enabling the Deaf and Hard of Hearing (DHH) community to access communication, education, and cultural identity [1]. However, most national sign languages, including Thai Sign Language (TSL), still lack standardized vocabulary in many academic and professional domains. In specialized fields such as print design, terms like “font,” “die-cut,” and “layout” often have no formal sign equivalents, which creates persistent barriers to inclusive education [2, 3].

DHH learners in design-related disciplines encounter particular challenges when engaging with domain-specific concepts. In the absence of standardized signs, instructors often rely on fingerspelling, gesture improvisation, or code-switching across spoken and signed languages. These compensatory methods, while practical, can lead to cognitive overload and reduced learning efficiency [4]. As shown in Table 1, these barriers impact both conceptual understanding and learner confidence, limiting full participation in the educational process.

While institutional bodies are typically responsible for formalizing sign vocabulary, the rapid evolution of technical language in education suggests a need for participatory strategies that empower educators and communities to co-develop usable signs [5].

Visual-spatial learning strategies have proven highly effective for DHH learners, aligning with their perceptual strengths and enhancing engagement, memory, and comprehension [6]. Technological advancements such as immersive learning environments offer new possibilities for self-paced, interactive, and multimodal instruction that supports diverse learning needs. Platforms like Spatial.io provide customizable, visually rich environments where learners can interact with content in a flexible and accessible manner [7].

Table 1. Learner evaluation scores on media usability and comprehension

Challenge	Description	Impact on Learning
1. Lack of Domain-Specific Vocabulary	Most sign languages lack established signs for design-specific terms such as “layout” or “vector” .	Learners struggle to understand or discuss key concepts, limiting technical fluency.
2. Limited Access to Specialized Instructors	Few educators are trained in both design and sign language.	Miscommunication occurs, reducing instructional clarity and learner engagement.
3. Over-Reliance on Text-Based Materials	Instructional content is often heavily text-based.	Learners may experience cognitive overload and difficulty accessing core information.
4. Minimal Use of Interactive or Immersive Media	Traditional classrooms rarely use interactive platforms.	Reduced motivation and hands-on learning opportunities for visual/manual learners.
5. Inconsistent Sign Usage Across Contexts	Signs may vary by region or educator.	Learners may internalize conflicting or incorrect concepts, affecting content mastery.
6. Lack of Peer Collaboration in Visual Formats	Limited collaborative opportunities in visual-first formats.	Learners miss out on design critique, group problem-solving, and language reinforcement.

This research aims to address the gap in domain-specific sign language education by developing an immersive learning environment tailored to DHH learners in the context of print design. The platform employs a hybrid instructional design approach, combining the systematic structure of the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) model with the empathy-driven mindset of Design Thinking. This integration ensures that the

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instructional flow remains learner-centered while meeting pedagogical goals.

The objectives of this research are as follows:

(1) To design and implement an immersive learning environment on Spatial.io for specialized sign vocabulary in print design.
(2) To develop interactive instructional media using animated flashcards, sign language videos, and self-assessment tools.
(3) To evaluate learner satisfaction, perceived usability, and the platform' s effectiveness in supporting equitable education for DHH learners.

II. Literature Review

A. Immersive Learning Environment for Deaf Learners

Immersive Learning Environments (ILEs) are reshaping modern education by using technologies like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) to create engaging, multi-sensory experiences. Platforms such as Spatial.io allow educators to build interactive 3D classrooms that promote collaboration, visual learning, and spatial awareness [8]. These environments support experiential, project-based learning and are especially effective for learners who benefit from visual and hands-on engagement [9].

For Deaf and Hard-of-Hearing (DHH) learners, Immersive Learning Environments (ILEs) offer significant improvements in accessibility. Unlike conventional e-learning platforms, immersive environments integrate visual–spatial interfaces and gesture-based interactions, enabling real-time communication and feedback [10]. This allows DHH learners to actively participate in the learning process without relying on auditory channels. Systems such as the DAVEE VR classroom and gesture-controlled XR applications have demonstrated increased learner agency and engagement [11, 12].

Immersive tools also align with the Universal Design for Learning (UDL) framework by offering multiple modes of content delivery. Features such as motion design, spatial mapping, and interactive simulations help reduce cognitive load and support knowledge retention [13]. This is especially beneficial in technical or abstract subjects, where visual demonstration enhances comprehension.

Complementing immersive platforms, the integration of sign language into digital applications further enhances accessibility. Innovations using frameworks like Media Pipe and Flutter have enabled real-time sign recognition, interactive tutorials, and multi-language support [14]. However, recent advancements in gesture recognition have expanded beyond these frameworks, Wang *et al*. [15] proposed a glove-based static sign recognition system enhanced by a self-attention mechanism, while Buribaye *et al*. [16] developed a real-time continuous sign language recognition model using YOLOv8n and 2D Convolutional Neural Networks (CNNs) for the Kazakh Sign Language (QazSL). Furthermore, a 2025 survey highlighted that ensemble and transformer-based architectures now outperform traditional CNN models in accuracy and robustness, indicating rapid evolution in AI-driven gesture understanding. These technologies not only bridge communication gaps but also empower DHH learners to engage deeply with subject-specific content. Collectively, immersive and sign-based technologies offer a powerful solution to promote equitable, inclusive education [17].

While immersive technologies such as VR have shown great potential, several studies have reported challenges for DHH learners, including visual fatigue, navigation difficulty, and sensory overload [18]. Therefore, this study adopted a screen-based immersive environment accessible via smartphones and computers, avoiding VR headsets to ensure usability, comfort, and accessibility for all learners.

B. Specialized Sign Language in Professional Domains

While sign language is recognized as a complete and natural language, most existing systems emphasize everyday vocabulary, leaving a significant gap in specialized terms across professional domains. This lack of domain-specific vocabulary presents critical barriers for Deaf individuals in both education and employment, especially in science, engineering, healthcare, law, and design. Projects such as *TechWhiz* have developed glossaries to translate scientific and technical terminology into sign language, while smart-glasses-based sign-to-text tools and gesture recognition systems support real-time communication in technical settings [18, 19]. In healthcare, video databases explain terms like "immunization" and "pandemic," and in law, efforts are underway to standardize signs for "testimony" and "witness," ensuring Deaf individuals can fully participate in legal processes [20].

Despite the growing number of Deaf learners in creative fields, specialized vocabulary in art and design remains limited, with essential terms like "font" and "layout" often lacking agreed-upon signs. Recent efforts have focused on co-creating sign sets with Deaf learners and professionals to fill these gaps, especially in visual communication [21]. Similarly, in business and finance, terms like "investment" and "profit" are beginning to appear in sign-supported e-learning modules that enhance access to vocational and entrepreneurship training. These developments illustrate a growing recognition of the need for specialized sign language in creating equitable learning and professional environments. Co-creation with Deaf communities ensures not only linguistic relevance but also empowers users through active participation in the design of accessible communication tools [22].

C. Deaf Learner

DHH learners often excel through visual-spatial learning strategies, which emphasize visual aids, spatial reasoning, and hands-on engagement rather than auditory-sequential methods. Silverman noted that such learners benefit most from instructional designs that utilize visualization and interaction, as opposed to rote memorization or phonics [23]. In immersive learning environments, like those using Virtual Reality (VR), visual cues such as color paths or rotational markers—can enhance spatial comprehension and task-solving skills [24]. Likewise, digital haptic feedback has shown promise in helping learners, including those with visual impairments, to mentally map spatial layouts, translating 2D images into meaningful 3D understanding [25]. These multimodal techniques not only support the cognitive strengths of DHH learners but also align with universal design principles that advocate for accessible, multisensory education.

D. Print Design

Print design relies on technical vocabulary such as "die-cut," "vector," "bleed," and "layer," all of which are critical in communicating and executing design tasks accurately. These terms span traditional and digital workflows, where, for example, "die-cut" refers to precision-cutting used in packaging, and "vector" enables image scalability without quality loss [26, 27]. However, DHH learners often lack access to sign language equivalents for these terms, limiting their conceptual understanding. Research has shown that integrating visual-spatial learning strategies, including virtual reality and contextualized instruction, can significantly enhance comprehension for DHH students [28]. Additionally, frameworks like the Developmental Ease of Language Understanding (D-ELU) model emphasize early and meaningful engagement with language to support vocabulary growth and cognitive development [29].

To address these challenges, recent advancements in sign-based media have made it possible to deliver domain-specific vocabulary through interactive and inclusive platforms. Gesture recognition systems, such as those built using React and MediaPipe, enable real-time sign detection that bridges communication gaps in learning environments [30]. These innovations, when co-designed with the Deaf community, not only increase access but also empower DHH learners to participate fully in technical education and professional contexts.

E. Instructional Design

In designing learning experiences that are both effective and inclusive, educators increasingly turn to structured design frameworks that center the needs of learners. Among these, models such as ADDIE and Design Thinking have proven particularly influential, offering systematic yet flexible approaches that support iterative development grounded in real user needs. The ADDIE model comprising Analysis, Design, Development, Implementation, and Evaluation has long been a cornerstone in instructional media design, especially in online and blended learning environments [31, 32]. In parallel, Design Thinking emphasizes empathy, ideation, and prototyping to creatively solve problems, making it especially effective in addressing the needs of diverse learners [33–35].

Core elements such as empathy, prototyping, and feedback loops play a pivotal role in creating instructional content that is both accessible and learner-centered. Empathy enables designers to deeply understand the perspectives, challenges, and contexts of their learners particularly those from underrepresented or specialized groups thereby informing more relevant and inclusive solutions [36]. Techniques like user persona development, field observations, and empathic interviews provide valuable insights into learners' behaviors, motivations, and learning preferences. Design frameworks such as the Double Diamond model place empathy at the heart of every phase, guiding the creation of educational experiences that are not only functional but also emotionally resonant, contextually appropriate, and impactful in real-life learning scenarios [37, 38].

III. Methodology

A. Research Design and Participants

This study employed a qualitative Research and Development (R&D) methodology, grounded in Human-Centered Design and Participatory Design principles. The research aimed to co-develop an immersive learning platform for domain-specific sign language acquisition tailored to Deaf learners in the field of print design. The study was conducted through iterative phases, including a pre-design pilot phase and a usability testing phase, involving observation, feedback collection, and co-design activities.

In the usability testing phase, participants consisted of 250 DHH learners recruited from multiple schools and vocational colleges in Thailand' s Central region, which serves as a national hub for sign language education. The participants included students enrolled in print design programs as well as those with an interest in design-related fields. Purposive sampling was employed to ensure relevance to the study context and active participation in media co-creation.

B. Data Collection and Instruments

Data were collected during three main stages: pre-design, mid-development, and post-implementation. In the pre-design stage, participants included 30 DHH students enrolled in a print design program at a vocational college in Thailand. This pilot group was selected through purposive sampling to support initial needs analysis, instructional design refinement, and early prototype testing.

Key instruments included:

- **Observation protocols**, used to capture learners' interaction patterns with the platform prototype.
- **User feedback forms**, comprising both 5-point Likert-scale items and open-ended questions, designed to evaluate usability, perceived clarity, and learner satisfaction.
- **Co-design workshop transcripts**, documenting the iterative collaboration process in vocabulary selection, gesture creation, and media content validation.

In the post-implementation usability testing stage, the developed platform was evaluated by 250 DHH learners recruited from multiple schools and vocational colleges in Thailand' s Central region. This larger sample was used to assess platform usability, learning engagement, and overall user experience. Quantitative data were collected primarily through structured questionnaires, while qualitative feedback was gathered through open-ended responses.

In addition, the instructional media were developed based on a validated vocabulary set of domain-specific sign language tailored for print design. This vocabulary set was co-created through a participatory process using the D-SIGN Model, a five-step framework for developing specialized sign language: Gap Mapping, Prototype Design, User Testing, Sign Refinement, and Distribution. Its outputs were validated by experts and served as the foundational content for this study' s media development, including flashcards and sign video clips.

To ensure research ethics and data protection, informed consent was obtained from all participants, and personal identifiers were anonymized. The study followed institutional guidelines on research with human participants and emphasized confidentiality throughout the process. Qualitative data from the pilot stage (observations, workshops, and open-end responses) were analyzed using thematic coding to identify recurring user needs, preferences, and design feedback. These insights informed successive refinements of the platform interface and learning content.

These insights informed successive refinements of the platform interface and learning content. Building on these refinements and to ensure technical reliability during implementation phase**,** the immersive learning activities were conducted using the *Personal Plan* of Spatial.io (non-commercial educational use). The platform was accessed via personal computers and smartphones using standard web browsers. This plan supports up to fifty concurrent users and provides sufficient storage capacity for sign language media and collaborative participation, ensuring accessibility and stability for group-based immersive learning among Deaf and Hard of Hearing (DHH) participants.

C. Instructional Design Framework

The instructional design process was guided by a hybrid approach, integrating the systematic structure of the ADDIE model with the empathy-driven flexibility of Design Thinking. This combination allowed the research team to align pedagogical goals with learner-centered insights, particularly addressing the needs of Deaf learners engaging with technical sign vocabulary in print design. Through iterative prototyping, user feedback, and continuous refinement, the platform development process remained anchored in both instructional rigor and contextual relevance. The hybrid model not only facilitated content structuring and visual planning but also enabled deeper collaboration with target users ensuring accessibility, engagement, and educational equity at every stage.

The instructional design process was guided by a hybrid model that integrates the structured phases of ADDIE (Analysis, Design, Development, Implementation, Evaluation) with the iterative, empathy-driven principles of Design Thinking.

- **Analysis**: Empathy interviews and contextual inquiry were conducted with Deaf learners to understand communication barriers and cognitive preferences. A domain vocabulary list (e.g., “font,” “die-cut”) was identified through curriculum review and learner feedback.
- **Design**: Learning zones and media content were mapped out with user input. Low-fidelity storyboards and interactive wireframes were co-created and validated by participants to ensure accessibility.
- **Development**: Interactive media (flashcards, looped sign videos, self-check quizzes) were produced and embedded into an immersive environment on Spatial.io. Sign language gestures were reviewed for clarity by a DHH consultant.
- **Implementation**: Participants engaged with the prototype in a self-paced learning session. Prior to the session, a short orientation was provided through an announcement and a brief sign language video that guided participants on how to navigate and interact within the immersive classroom. The platform was accessed using private entry codes with embedded QR codes linking to content.
- **Evaluation**: Formative evaluation included post-session feedback and in-situ usability observations. User responses guided minor interface and content adjustments.

This hybrid instructional design approach align pedagogical goals with DHH learners real experiences and preferences of, ensuring conceptual understanding and equitable access to knowledge. A follow-up phase was planned over two academic semesters to observe learners’ progress in skill retention and platform engagement. The first semester of longitudinal tracking has already been completed, with findings to be reported in a subsequent study

IV. Results

A. Immersive Platform Development on Spatial.io

The immersive learning platform was designed and implemented using Spatial.io, a browser-based 3D environment that allows for interactive, multi-user exploration. The platform was developed with the goal of supporting DHH learners in acquiring specialized vocabulary related to print design, using a spatial layout that enhances visual learning and sign-based interaction. To align with both pedagogical intent and learner engagement, the platform was structured into four themed learning zones, each fulfilling a distinct function in the learning journey:

1) Inspire zone—motivation and context building

Fig. 1. Welcome area.

This introductory space serves as the entry point to the immersive experience. Before entering this zone, learners first pass through a small Welcome Area (Fig. 1) that introduces the Immersive Sign Language Classroom. This area features a welcome sign with visual and sign language elements, and a short video explaining how to navigate and interact within the immersive classroom. A simple map illustrates the four learning zones, and QR codes allow learners to download worksheets and self-assessment quizzes. This Welcome Area helps orient DHH participants, ensuring they can access and explore the learning environment independently. It features welcoming visuals, ambient background design, and inspirational quotes from Deaf learners. The zone was created to build a sense of belonging, cultural validation, and motivation. Its design encourages emotional connection with the learning space and promotes a sense of value and identity among learners as part of a digital learning community. Fig. 2 presents an overview of the Inspire Zone.

Fig. 2. Inspire zone.

2) QuickSign zone—foundational vocabulary and pre/post quiz

This zone focuses on basic domain-specific vocabulary using interactive flashcards and self-assessment tools. Learners can review terms such as "font," "bleed," and "vector" through animated sign language cards accompanied by pre- and post-tests. The environment is optimized for fast recall and low cognitive load, enabling learners to engage in short, focused learning cycles. Fig. 3 illustrates the layout and media elements used in this zone.

Fig. 3. QuickSign zone.

3) DeepSign lab—complex gesture learning and practice

Designed for more complex vocabulary, this zone supports learning of terms that require sequential gestures or multi-part explanations. Learners interact with looped instructional videos, hands-on sign practice, and visual scaffolds that deconstruct terms such as *"die-cut," "layer,"* and *"layout"*. This environment encourages deeper learning through repetition, reflection, and experimentation particularly for signs not yet standardized. An example of this zone is shown in Fig. 4.

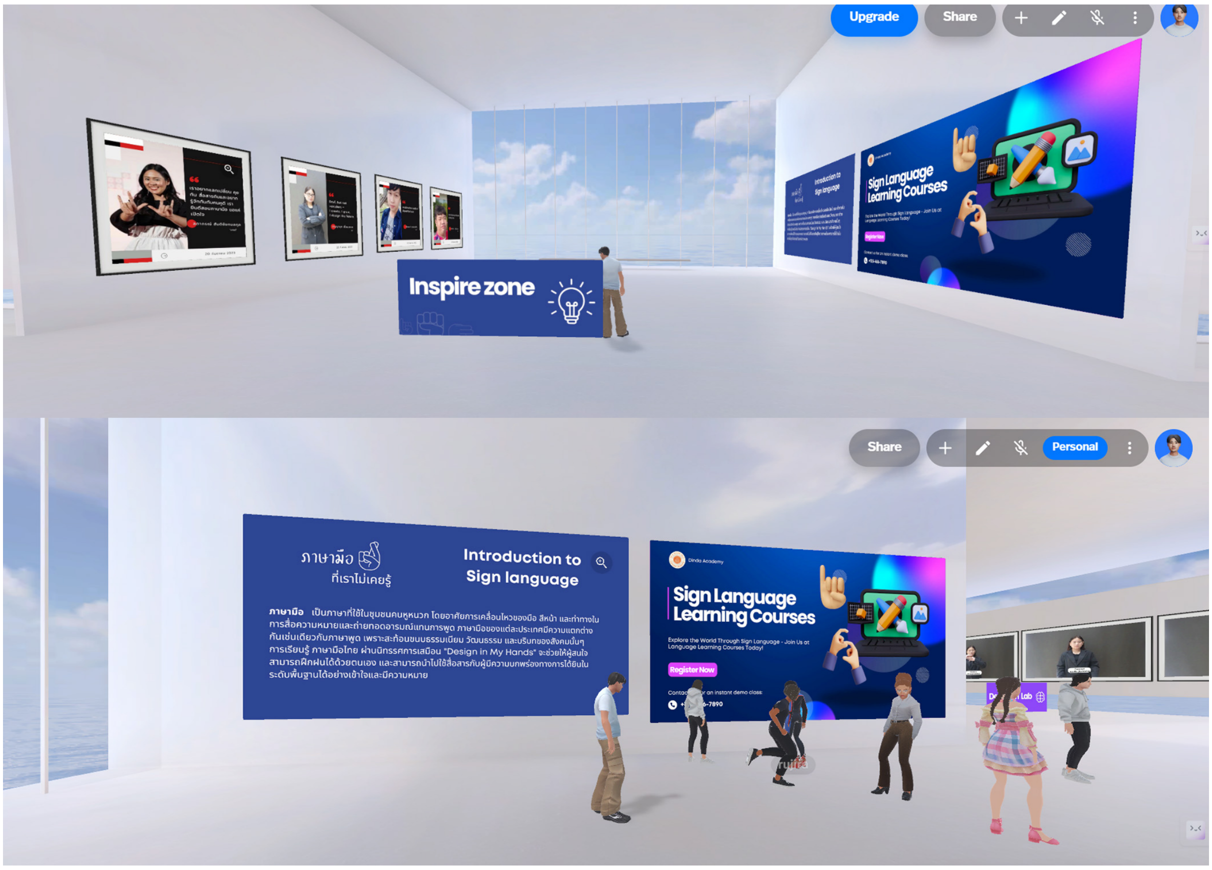

Fig. 4. DeepSign lab.

4) *Gallery zone—showcase and reflection*

This final zone offers learners a space for reflection and sharing. It showcases artifacts generated during the learning sessions, including photo documentation, video recordings of learner-performed signs, and co-created media from workshops. The Gallery Zone promotes ownership, recognition, and community visibility while serving as a public-facing archive of learner contributions. Fig. 5 highlights the visual layout of this collaborative space.

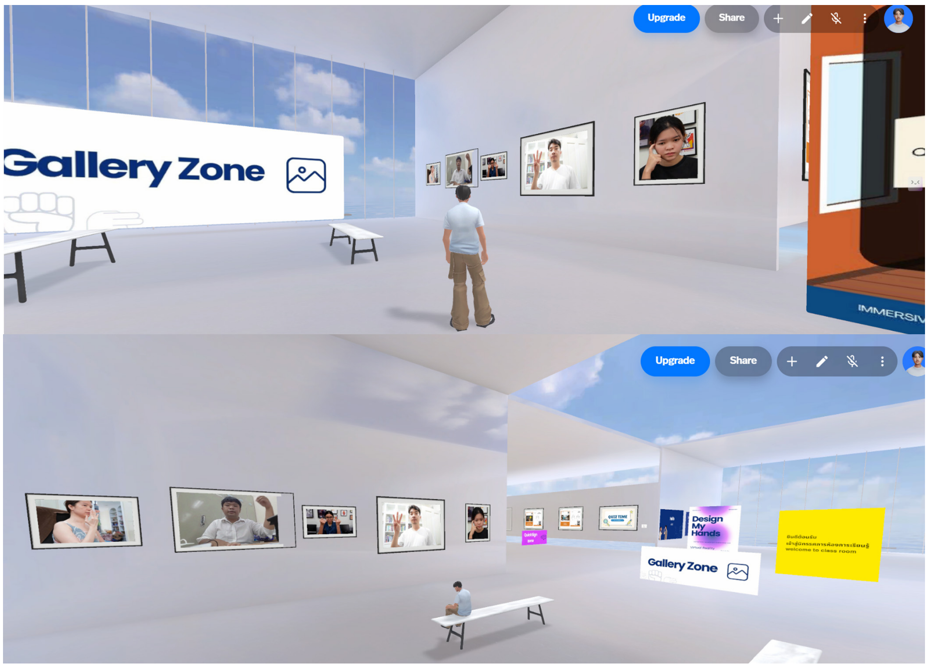

Fig. 5. Gallery zone.

Together, these four zones form a cohesive and immersive structure designed to align with the cognitive styles of DHH learners. The use of Spatial.io enabled the creation of a dynamic, accessible environment tailored to the needs of students in the print design discipline, integrating spatial, visual, and interactive learning elements.

B. *Instructional Media and Learning Content*

To support domain-specific sign language acquisition for DHH learners in the context of print design, this research developed a set of instructional media grounded in visual pedagogy and inclusive communication principles. All media were integrated into the Spatial.io platform and designed for self-paced, immersive interaction.

1) *Types of media developed*

The instructional materials comprised three main components:

- **Animated Flashcards:** Featuring illustrated terms alongside looping sign animations for quick reference and recall. Each card was paired with a representative image to reinforce semantic meaning (Fig. 6).
- **Sign Language Videos:** Developed in two levels: Basic Vocabulary (e.g., “font,” “paper,” “print”) and Complex/Technical Vocabulary (e.g., “die-cut,” “bleed,” “vector”) Videos were recorded with a Deaf signer and edited for clarity using neutral backgrounds, close framing, and looping playback (Fig. 7).
- **Self-Check Quizzes**: Designed as low-stakes formative assessments, quizzes allowed learners to review and reflect on vocabulary comprehension. Each quiz included visual multiple-choice items and sign recognition tasks.

Fig. 6. Sample animated flashcard.

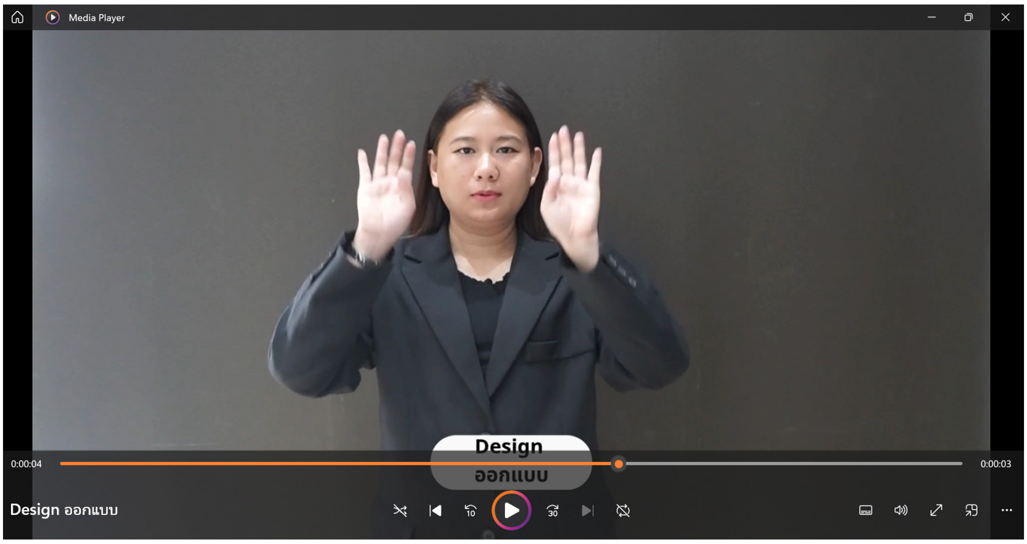

Fig. 7. Sign language videos.

2) *Instructional design approach*

All media were created under the principles of UDL, ensuring accessibility through:

- **Visual clarity**: High-contrast visuals, large gesture framing, and consistent iconography
- **Animation loops**: Seamless loops for sign motion to support repeated observation
- **User interaction**: Tap-to-reveal signs, hover effects, and embedded feedback prompts to enhance engagement

Content was differentiated by complexity, with a tiered structure dividing basic, intermediate, and technical vocab. This allowed learners to progress at their own pace and revisit foundational terms as needed.

3) Curricular relevance

All sign terms were selected in alignment with the course content of the Print Design curriculum, including terminology extracted from course syllabi, textbooks, and studio instruction. The instructional media served not only to support Deaf learners but also to standardize visual explanations of technical terms across all users. This structured and inclusive design ensured that the learning content was not only engaging but also pedagogically relevant, linguistically accurate, and aligned with professional standards in print design education.

C. User Evaluation

To assess the usability, clarity, and educational value of the immersive platform and instructional media, user evaluation was conducted in three dimensions: expert review, learner evaluation, and learner feedback and satisfaction.

1) Expert review

To ensure content accuracy, pedagogical soundness, and cultural appropriateness, an expert review was conducted prior to learner testing. The panel consisted of three professionals with complementary expertise:

Expert A: A certified Thai Sign Language (TSL) interpreter with over 10 years of experience working with Deaf communities and in educational interpreting;

Expert B: A university lecturer in instructional media and technology, specializing in digital learning design for diverse learners;

Expert C: A faculty member in inclusive and special education, with a research background in accessible curriculum development.

The results of the expert evaluation are summarized in Table 2. Overall, the evaluation indicated a high level of agreement among experts regarding the quality and appropriateness of the developed instructional media and immersive learning platform. The overall mean score was 4.77, which was interpreted as the highest level of suitability.

Table 2. Expert evaluation results using a 5-point Likert scale

Evaluation Criteria	Mean ($\bar{x}$)	SD	Interpretation
1. Accuracy of domain-specific vocabulary	4.80	0.45	Highest
2. Relevance to print design context	4.60	0.55	High
3. Instructional clarity and logical flow	4.67	0.47	High
4. Accessibility for Deaf learners	4.87	0.35	Highest
5.Visual design and media quality	4.73	0.50	High
6.Cultural and linguistic appropriateness of signs	4.93	0.26	Highest
7.Potential for classroom application	4.80	0.41	Highest
Total Average	**4.77**		**Highest**

Qualitative insights from expert feedback included:

- The accuracy of sign gestures was praised, especially for technical terms like “bleed” and “layout,” which had been co-developed with Deaf participants using the D-S²IGN model.
- The looped video structure was noted as particularly beneficial for learners needing repetition to retain multi-step gestures.
- Visual hierarchy and labeling on flashcards were found to be mostly effective, though two reviewers recommended slightly slowing animation sequences for longer signs.
- Experts affirmed the platform’ s alignment with UDL principles, citing flexibility, clarity, and multi-modal support as key strengths.

This expert validation phase not only ensured technical and cultural rigor but also reinforced the platform’ s pedagogical readiness before broader learner deployment.

2) Learner evaluation

DHH students from a print design program in a vocational college in Thailand participated in the study. A structured 5-point Likert-scale questionnaire was used to evaluate their experience with the platform and learning materials.

The results indicate high overall satisfaction with the platform’ s usability and clarity. Learners found the visual content helpful in understanding technical vocabulary and appreciated the self-paced, interactive design. The highest score was observed in the category of “Visual clarity and sign animation,” suggesting the importance of multimodal content delivery for Deaf learners.

3) Learner feedback and satisfaction

Qualitative feedback was collected through open-ended questions and post-session reflections. Three major themes emerged:

- **Enhanced Understanding**: Learners reported that the animated videos helped them “see the meaning” of unfamiliar words such as *die-cut* or *vector*.
- **Appreciation for Interaction**: Many participants expressed enthusiasm about being able to “practice repeatedly” and “test themselves” through self-check quizzes.
- **Suggestions for Improvement**: Learners suggested adding more sign vocabulary, integrating voiceovers for mixed-ability groups, and allowing content bookmarking for personalized learning.

Overall, learner feedback indicated a high level of acceptance and positive perception toward the platform, with many participants expressing interest in using similar immersive, sign-integrated learning environments in other courses and supporting its integration into formal curriculum delivery.

V. Discussion

This study aimed to develop an immersive learning platform integrating domain-specific sign language for print design, addressing the longstanding accessibility gap for DHH learners in technical education. The immersive environment on Spatial.io, combined with instructional media including animated flashcards, looped sign language videos, and self-assessment tools, provided an inclusive learning experience that responded to both cognitive and cultural needs of the learners.

The results from expert evaluation presented in Table 2 revealed a high level of quality across all six criteria, with an average score of 4.77 out of 5, especially highlighting the platform' s accessibility, instructional clarity, and cultural appropriateness. Notably, the criterion "Cultural and linguistic appropriateness" received the highest score of 4.93, indicating strong alignment with the communication practices of the DHH community. This confirms that the media successfully conveyed technical vocabulary such as "die-cut," "layer," and "layout" in a form that was not only understandable but also linguistically appropriate.

Table 3. Learner evaluation scores on media usability and comprehension (n = 250)

Learner Evaluation Item	Mean ($\bar{x}$)	SD	Interpretation
1. Ease of understanding sign language content	4.63	0.52	Highest
2. Clarity of visuals and animations	4.73	0.45	Highest
3. Usefulness of flashcards and quizzes	4.67	0.49	Highest
4. Engagement with the immersive learning environment	4.57	0.58	Highest
5. Overall satisfaction with the platform	4.70	0.46	Highest
Total Average	**4.66**		**High**est

Learner evaluation further supported these findings. As reflected in the mean scores reported in Table 3, learners demonstrated the highest levels of perceived usability, comprehension, and engagement across all evaluation items. High mean scores in ease of understanding sign language content, clarity of visuals and animations, and usefulness of flashcards and quizzes indicate that the instructional media effectively supported the acquisition of domain-specific vocabulary. In addition, strong engagement with the immersive learning environment and high overall satisfaction suggest that the screen-based immersive design contributed positively to learner motivation and learning experience.

The platform' s success can be attributed to the application of a hybrid instructional design approach, combining the structured phases of the ADDIE model with the empathy-driven flexibility of Design Thinking. Through contextual inquiry, co-design workshops, and iterative prototyping, the development process remained centered on the learners' experiences and feedback. By using outputs derived from the D-S²IGN Model previously validated and co-developed with Deaf users the vocabulary used in the platform ensured both accuracy and cultural sensitivity.

Despite these achievements, the study has certain limitations. While the usability evaluation involved 250 DHH learners from multiple institutions, the pilot testing and co-design activities were conducted with a smaller group during the early design phase. In addition, the evaluation primarily focused on short-term usability and learning experience, which may not fully capture long-term learning retention or performance outcomes. Moreover, instructors were not yet fully integrated into the trial process, limiting insights into classroom-level implementation. Future work should address these gaps by extending the implementation period, enhancing learning analytics capabilities, and collaborating with educational institutions to explore broader classroom and curriculum integration.

Ultimately, this study affirms that immersive platforms, when co-created with users and grounded in accessible media design, hold the potential to promote equitable education and professional readiness for DHH learners in specialized fields like print design.

VI. Conclusion

This study contributes to inclusive digital pedagogy by presenting an empirically grounded approach to integrating domain-special sign language into immersive learning environment for print design education. The instructional ecosystem developed on Spatial.io comprising structured learning zones, gesture-based instructional media, and interactive self-assessments demonstrates how learner-centered and participatory design can effectively address accessibility barriers in technical education for DHH learners. The use of expert-validated vocabulary and co-created sign language media highlights the importance of cultural and linguistic alignment in the design of inclusive learning systems, reinforcing the value of community-informed instructional development.

From a design and educational perspective, the findings demonstrate that immersive, screen-based learning environments integrated with specialized sign language can serve as scalable tools for inclusive technical education. The proposed model highlights how immersive platforms can support equitable access to professional knowledge without reliance on high-barrier technologies such as VR headsets, and offers implications for instructional design, educational practice, and inclusive education policy, particularly in vocational and creative disciplines.

Despite the expanded usability evaluation with 250 DHH learners from multiple institutions, this study has limitations related to scope and implementation. The evaluation emphasized short-term usability and learning experience rather than long-term learning outcomes, and the current version of the Spatial.io platform lacks automated learning analytics, requiring alternative data collection methods. Future research should extend implementation duration, strengthen instructor involvement in classroom contexts, enhance analytics capabilities, and apply the model across additional vocational domains. Overall, the study affirms that inclusive educational technologies are most effective when co-developed with the communities they are intended to serve.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

P.T. conceptualized the study, developed the immersive learning platform and instructional media, conducted data collection and analysis, and prepared the original draft of the manuscript. R.P. and V. S. provided academic supervision and reviewed the manuscript. All authors have read and approved the final version of the manuscript.

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REFERENCES

[1] G. Georgiou, "Sign language and the visual modality: Language in the eyes," *Linguistics and the Human Sciences*, vol. 17, no. 1–2, pp. 87–104, 2023.
[2] A. Sandler and W. K. Wilbur, "A language in space: The story of israeli sign language," *Lawrence Erlbaum Associates*, 2006.
[3] S. Chaiwan and P. Phonsuwan, "The current situation and challenges in Thai sign language development," *Journal of Linguistics and Language Teaching*, vol. 9, no. 1, pp. 15–27, 2021.
[4] M. Skyer, "The visual politics of deaf education: human-centered design for inclusive pedagogy," *Deafness & Education International*, vol. 24, no. 4, pp. 221–235, 2022.
[5] E. Krasavina, O. Frolova, and A. Yudina, "Strategies for Meta-communication in digital deaf education," *Education and Self Development*, vol. 18, no. 3, pp. 10–22, 2023.
[6] J. Hernández, S. Torres, and V. Navarro, "Participatory sign creation with deaf communities: Guidelines from the field," *Universal Access in the Information Society*, vol. 23, no. 1, pp. 77–92, 2024.
[7] F. Alfina, M. Gunarhadi, and H. Widyastono, "The effectiveness of multimedia learning for deaf students in inclusive classrooms," *Journal of Special Education Technology*, vol. 36, no. 2, pp. 67–75, 2021.
[8] S. Meher and R. Meher, "Immersive learning and the SAMR model: Redefining education through virtual spaces," *Journal of Educational Technology Innovation*, vol. 11, no. 2, pp. 45–52, 2024.
[9] M. Peterson *et al*., "Virtual robotics training using VR simulations: Impact on learning and confidence," *International Journal of Engineering Pedagogy*, vol. 8, no. 3, pp. 100–109, 2022.
[10] K. Chan, M. Lau, and T. Fong, "Art beyond Canvas: Using VR for visual arts education," *Arts Education Review*, vol. 4, no. 1, pp. 12–20, 2016.
[11] N. Paudyal *et al*., "DAVEE: A virtual reality classroom for deaf students," *Computers & Education*, vol. 138, pp. 102–112, 2019.
[12] A. Boussemart, K. Vasudevan, and R. Bajcsy, "Bimanual gesture-based interaction in virtual learning spaces," *IEEE Trans. Vis. Comput. Graph.*, vol. 10, no. 3, pp. 276–283, 2004.
[13] I. Lytvynova, "Overcoming barriers in immersive learning: Cognitive, technical, and temporal challenges," *Technology and Education Journal*, vol. 15, no. 1, pp. 33–41, 2023.
[14] A. Novaliendry, R. F. Ramadhani, and M. R. Putra, "Flutter-based sign language learning app for special needs education," *Journal of Mobile Learning and Innovation*, vol. 9, no. 2, pp. 77–84, 2023.
[15] Y. Wang, H. Jiang, Y. Sun, and L. Xu, "A static sign language recognition method enhanced with self-attention mechanisms," *Sensors*, vol. 24, no. 21, 6921, 2024.
[16] Z. Buribaye *et al*., "Enhancing Kazakh sign language recognition with BiLSTM using YOLO keypoints and optical flow," *Applied Sciences*, vol. 15, no. 10, 5685, 2025.
[17] A. Chong, K. T. Wong, and V. L. S. Kong," Teknologi Imersif dalam Pendidikan Matematik Murid Ketidakupayaan Pendengaran: Naratif daripada Realiti Terimbuh (AR) hingga ke Metaverse," *Journal of Research, Innovation, and Strategies for Education (RISE)*, vol. 2, no. 4, pp. 66–82, 2025.
[18] A. Deoghare, N. Pawar, and R. Thakare, "Gesture recognition for deaf education using react and MediaPipe," in *Proc. Int. Conf. on AI in Education*, pp. 132–137, 2024.
[19] P. Ezra, Y. Ben-David, and T. Kakon, "Deep learning framework for dynamic gesture recognition in Israeli sign language," *Computer Vision in Inclusive Education*, vol. 7, pp. 45–59, 2024.
[20] M. Wang and E. Sahagun, "Real-time machine learning-based translation between sign and spoken languages," *ACM Trans. Access. Comput.*, vol. 12, no. 1, pp. 1–18, 2024
[21] M. Escudeiro, C. Pedro, D. Silva, and S. Escudeiro, "TechWhiz: A sign language glossary for teaching scientific and technical concepts to deaf students," *Education Sciences*, vol. 12, no. 9, 614, 2022. doi: 10.3390/educsci12090614.
[22] P. Zhang, W. Liang, C. Zhang, and Y. Zhao, "Smart glasses-based real-time translation system for sign language recognition," *Sensors*, vol. 23, no. 4, 1965, 2023. doi: 10.3390/s23041965
[23] A. Sánchez, R. R. Pradera, A. Sánchez-Rada, A. Haya, and M. P. Rodríguez, "Inclusive user interfaces prioritizing sign language over spoken language: A design perspective," *Universal Access in the Information Society*, vol. 21, pp. 695–710, 2022. doi: 10.1007/s10209-021-00827-9
[24] M. Meulder, D. Landuyt, and R. Omardeen, "Lessons in co-creation: the inconvenient truths of inclusive sign language technology development," arXiv Preprint*,* arXiv:2408.13171, 2024.
[25] European Union of the Deaf (EUD), "SignON Project: Bringing Machine Translation to the Deaf Community," SignON Dissemination Report*,* 2023.
[26] A. Srivastava, "Disability, inclusion and the RPwD act 2016: A critical perspective," *Indian Journal of Social Development*, vol. 24, no. 1, pp. 1–13, 2024.
[27] V. Kaushik, "Inclusive education in NEP 2020: From policy to practice," *International Journal of Educational Research*, vol. 9, no. 3, pp. 44–52, 2024.
[28] D. Lillo-Martin *et al*., "Family ASL: Supporting early exposure for deaf children," *Sign Language Studies*, vol. 21, no. 4, pp. 561–587, 2021.
[29] J. Branyon *et al*., "Functional multi-layer die-cut packaging," *Journal of Packaging Science*, 2015.
[30] F. Romano, "Digital imaging for print," *Graphic Arts Education Research*, 1997.
[31] C.-H. Chen *et al*., "Visualized cues for enhancing spatial ability training in virtual reality," *Int. J. of VR Education*, 2022.
[32] M. Rudner and E. Holmer, "D-ELU model: Working memory in sign language acquisition," *J. Deaf Stud. Deaf Educ.*, 2016.
[33] N. Deoghare *et al*., "Real-time gesture recognition using MediaPipe," in *Proc. IEEE Int. Conf. Signal Process.*, 2024.
[34] R. Dam and T. Siang, "5 stages in the design thinking process," *Interaction Design Foundation*, 2024.
[35] M. Shanks *et al*., *An Introduction to Design Thinking Process Guide*, Stanford University, 2015.
[36] A. Aldoobie, "The ADDIE instructional design model: A critical review," *Journal of Education and Practice*, vol. 6, no. 1, pp. 60–65, 2015.
[37] S. Dong, "Instructional design with ADDIE and rapid prototyping for blended learning," *Educational Technology Research and Development*, vol. 70, no. 3, pp. 1341–1365, 2022.
[38] Design Council, "Framework for innovation: The double diamond model," *Design Council*, 2005.