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MULTIMODAL LEARNING IN A METAVERSE-BASED GEOMETRY ENVIRONMENT: ENGAGEMENT AND SOCIAL PRESENCE AMONG DEAF AND HARD-OF-HEARING STUDENTS

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ABSTRACT

Aim/Purpose	Despite growing interest in metaverse-based education, empirical research on its accessibility and effectiveness for deaf and hard-of-hearing (DHH) learners remains virtually absent. This study addresses this critical gap by providing an empirical examination of how DHH students experience engagement, multi-modal interaction, and social presence in a metaverse-based geometry learning environment.
Background	Guided by self-determination theory, multimodal learning principles, and embodied social presence theory, this study examines how metaverse affordances align with DHH learners' visual-spatial strengths and communicative needs in geometry education.
Methodology	This research adopted an explanatory sequential mixed-methods design involving ten Malaysian DHH secondary students who participated in four metaverse-

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	based geometry lessons. Quantitative data were collected through questionnaires measuring engagement, visual-interactive features, and social presence. Qualitative follow-up interviews were conducted with five students.
Contribution	This study provides novel empirical evidence that metaverse environments, when designed with visual-gestural affordances, can effectively support inclusive STEM learning for DHH students, a population often underrepresented in educational technology research. Practical design principles for accessible metaverse instruction are discussed.
Findings	Students reported high engagement (M = 4.62), positive perceptions of visual-interactive features (M = 4.51), and strong social presence (M = 4.58). They valued 3D object manipulation, avatar customization, and spatial exploration, reporting that these features enhanced engagement and interest. A comparatively lower score for sustained attention (M = 4.10) indicated that visually rich environments require careful scaffolding to manage cognitive load.
Recommendations for Practitioners	Accessibility should be embedded from the outset. Interactive features such as 3D objects and avatars should serve clear pedagogical purposes. Collaborative tools should be intentionally structured with explicit task guidance. Teachers should provide explicit guidance, model navigation strategies, and introduce tools gradually.
Recommendations for Researchers	Future work should incorporate comparison conditions, longitudinal designs, and achievement-based measures. Researchers should investigate individual differences such as prior technology experience, working memory capacity, and communication preferences.
Impact on Society	The findings demonstrate potential for metaverse-based learning to support both conceptual understanding and social inclusion for DHH learners, contributing to more equitable and rigorous STEM education.
Future Research	Future studies should include larger, more diverse cohorts across schools and contexts, examine how avatar customization shapes motivation and identity, and evaluate advanced accessibility supports such as AI-supported signing avatars, gesture recognition, and adaptive captioning.

Keywords	metaverse, deaf and hard-of-hearing, embodied social presence, multimodal learning, geometry education, inclusive design

INTRODUCTION

The metaverse, conceptualized as an immersive, persistent, and interactive digital environment, is increasingly recognized as a transformative space for teaching and learning. By integrating virtual reality (VR), augmented reality (AR), artificial intelligence (AI), and the Internet of Things (IoT), metaverse platforms provide engaging, personalized, and collaborative learning experiences that extend beyond the spatial and temporal constraints of traditional classrooms (Almeman et al., 2025; Chamola et al., 2025; Onu et al., 2024; X. Zhang et al., 2022). Within these environments, students can interact with manipulable 3D models, virtual laboratories, and interactive simulations, which in turn support deeper conceptual understanding and improved knowledge retention (Aziz et al., 2025; Liu et al., 2025).

These affordances have been applied across diverse educational domains, including STEM, medical training, and language learning (Chen et al., 2024; Damaševičius & Sidekerskienė, 2024). Virtual laboratories allow students to conduct experiments in safe, flexible, and resource-efficient settings (Li

& Liang, 2024; Morsanuto et al., 2023), while medical education increasingly employs extended reality platforms for simulation-based training and collaborative case-based learning (Lewis et al., 2024; Yu et al., 2025). In language learning, metaverse-based environments have begun to draw on real-time communication tools and gamified activities to enhance participation and practice (Prabakaran et al., 2025).

A parallel body of work highlights the promise of the metaverse for equity and inclusion, particularly for learners with disabilities. Sghaier et al. (2022) reported significantly higher mathematics gains among students with multiple disabilities using a Moodle-integrated 3D metaverse compared to traditional classrooms. At the higher education level, Hadi Mogavi et al. (2023) found that disabled university students perceived well-designed "metaversity" environments as reducing participation gaps through features that foster recognition, empowerment, and psychological safety. Salem et al. (2024) further proposed an inclusive architecture that incorporates captioning, sign-language-enabled avatars, adjustable visual settings, and AI-based personalization to minimize barriers across diverse disability profiles.

For deaf and hard-of-hearing (DHH) learners specifically, visually rich, spatially oriented learning environments hold particular promise. Research indicates that DHH learners benefit when mathematics instruction foregrounds diagrams, dynamic 3D models, animations, and direct manipulation rather than dense text or lecture-only methods, particularly in geometry (Blatto-Vallee et al., 2007; Thom & Hallenbeck, 2021, 2022; Yurmalia & Hasanah, 2022). Yet in practice, these strengths are often underutilized. In Malaysia, for example, many DHH children have limited early exposure to natural sign language and first encounter school-based systems such as Manually Coded Malay (*Kod Tangan Bahasa Melayu,* KTBM) only upon entering primary school around age seven, constraining academic language development (Chong & Mohd Hussain, 2021).

Despite the growing body of research on metaverse-based learning in mainstream education and certain disability contexts (Chamola et al., 2025; Lee et al., 2023; Sghaier et al., 2022), three interconnected areas remain underexplored in DHH education: (a) how immersive, manipulable 3D environments support DHH learners' perceived understanding of and interest in geometry by leveraging visual–spatial affordances; (b) the conditions under which authentic social presence and peer collaboration can be achieved through visual and avatar-mediated interaction in the absence of auditory cues; and (c) the accessibility experiences of DHH students in metaverse platforms and the resulting design principles that best support their engagement and learning.

This study addresses these gaps by offering one of the earliest empirical examinations of metaverse-based geometry learning for DHH students. Integrating Self-Determination Theory, Multimodal Learning Theory, and Embodied Social Presence Theory into a unified analytical framework, the study investigates how DHH students experience autonomy, visual-spatial competence, and avatar-mediated relatedness in an immersive geometry environment. The findings contribute novel insights into the affordances and constraints unique to DHH learners in 3D metaverse settings, including high engagement and collaborative presence alongside challenges related to split visual attention and cognitive load.

LITERATURE REVIEW

LEARNING ENGAGEMENT THROUGH SELF-DETERMINATION THEORY

Student engagement is a multidimensional construct encompassing behavioral, emotional, and cognitive involvement in learning activities (Reschly & Christenson, 2012). Self-determination theory (SDT) provides a useful lens for understanding engagement, positing that it arises from satisfying three fundamental psychological needs: autonomy, competence, and relatedness (Ryan & Deci, 2000). For DHH learners, whose cognitive processing is predominantly visual-spatial, these needs are

especially critical in geometry education, a subject that relies heavily on visualization and spatial reasoning (Blatto-Vallee et al., 2007; Thom & Hallenbeck, 2021).

The metaverse has unique potential to support all three SDT needs concurrently (Gim et al., 2023; Ryan & Deci, 2020). Autonomy is fostered through avatar customization, self-directed exploration, and flexible pathways that let learners regulate their own pace and learning trajectory (Kang & Kim, 2020; Tinmaz & Singh Dhillon, 2024; Wu et al., 2023). Competence is strengthened when students directly manipulate 3D geometric objects in immersive environments. Alobaid et al. (2025) found significant improvements in spatial visualization ability following VR-based learning, while Romero et al. (2023) demonstrated that students could develop their own strategies for calculating volume and surface area through interactive 3D exploration. Relatedness is supported in shared virtual spaces where learners interact with peers and instructors via embodied avatars, creating a sense of being together and working jointly on tasks (Voinea et al., 2022). Compared with conventional online platforms, metaverse environments also offer higher levels of presence, flow, and fidelity, which can deepen immersion and sustain participation (Al-kfairy et al., 2024; Bali et al., 2024; Çelik & Baturay, 2024).

Avatars are one of the most defining features of the metaverse. They simulate real-world social interaction, enhance a sense of identity and agency, and serve as tools for communication and collaboration (Jande & Ibrahim, 2020; Wu et al., 2023; Zimmermann et al., 2023). Research indicates that avatar-mediated environments improve motivation and engagement by allowing learners to express themselves and interact through their digital representations (Al-Muqbil, 2024; Kang & Kim, 2020; Tinmaz & Singh Dhillon, 2024). In instructional contexts, avatars support real-time collaboration, shared 3D object construction, and joint problem-solving, thereby reinforcing both academic and social engagement (Tinmaz & Singh Dhillon, 2024). More advanced immersive systems that incorporate motion tracking and real-time feedback further strengthen cognitive and emotional engagement by synchronizing virtual activities with learners' physical actions (Alam et al., 2024; Shao et al., 2020).

However, recent work cautions that such technological affordances are effective only when embedded in strong pedagogy. In metaverse-based learning, pedagogical design has been shown to be a stronger predictor of engagement than technological features, and research on online courses similarly highlights teaching presence and instructional strategies as key drivers of sustained engagement rather than technological novelty alone (Pangsapa et al., 2023; Wang et al., 2021). Effective instructional design in immersive environments, therefore, needs to align activities with cognitive, affective, and psychomotor learning goals, incorporate clear objectives, structured tasks, and timely feedback, and use immersive tools to deepen rather than distract from learning (Mystakidis & Lympouridis, 2024).

Multimodal Resources: A More Integrated and Interactive Approach

Multimodality is central to deaf pedagogy because it integrates multiple modes in synergy, supporting access, understanding, and knowledge co-construction in digital learning environments for DHH students (Skyer, 2022). Consistent with this rationale, empirical studies show that multimodal strategies can enhance learning outcomes and critical thinking relative to traditional approaches, and these gains are not dependent on matching instruction to fixed learning-style categories (Arifin et al., 2025; Mohammed et al., 2024). In immersive settings, embodied interaction coupled with real-time feedback can further strengthen engagement during learning activities (Alam et al., 2024; Shao et al., 2020). For DHH students, mathematics instruction should therefore prioritize visually accessible, visual-spatial representations and coordinated visual supports that build on learners' visual processing strengths (Langdon et al., 2023; Skyer, 2022).

Immersive AR/VR learning environments can operate as high-density multimodal spaces by integrating manipulable 3D representations within navigable virtual contexts, enabling learners to select, ro-

tate, zoom, and explore mathematical forms in ways that align with the visual-spatial demands of geometry (Medina Herrera et al., 2024). Through embodied interaction, these environments also support dynamic transformations, including gesture-based control that enables natural 3D operations, such as rotation and translation, during object manipulation (M. Kim & Lee, 2016). Metaverse-oriented learning spaces further strengthen interactivity by providing immediate feedback loops that connect learners' actions to responsive system outputs, a mechanism associated with higher engagement and motivation in interactive learning (Damaševičius & Sidekerskienė, 2024).

Despite these advantages, multimodal richness can increase cognitive load when learners must process multiple information streams at once. For DHH learners, this burden is amplified because they often need to allocate visual attention across simultaneous visual inputs such as captions, interpreters, and instructional visuals (Luft & Brochu, 2023; Mather & Clark, 2012). In immersive and metaverse-like environments, unnecessary interface complexity and excessive on-screen movement can further add extraneous demands, reinforcing the need to streamline visual interaction and reduce avoidable attentional costs (T. Kim et al., 2023; Moro, 2023). Accordingly, design guidance for immersive learning emphasizes structured objectives, carefully sequenced tasks, and feedback mechanisms, supported by deliberate mediation choices and user-experience design that sustains engagement without overwhelming learners (Mystakidis & Lympouridis, 2024).

Embodied Social Presence in Virtual Learning: Building Connection and Community

Social presence, the sense of "being there" with others in a mediated environment, has evolved significantly since its original formulation in text- and audio-based systems (Short et al., 1976). Traditional frameworks, such as the Community of Inquiry model (Garrison et al., 1999), may be less specified for avatar-driven 3D learning contexts, where interaction is embodied and spatially situated. Embodied Social Presence (ESP) theory extends social presence by incorporating co-presence, mutual attention, behavioral interdependence, and emotional projection through avatar interaction (Mennecke et al., 2011; Oh et al., 2023; G. Zhang et al., 2022).

For DHH students, metaverse-relevant design is especially salient because communication is often anchored in visual-gestural channels. In sign-focused avatar work, the need to convey visually critical articulators is emphasized, including natural facial expressions and clear prioritization of the hands and eyes for sign clarity (Quandt, 2020). Empirically, an avatar-based mixed reality condition has been shown to produce higher co-presence and higher perceived emotional and behavioral interdependence than a conventional Skype/Meet baseline, suggesting that avatar-mediated interaction can strengthen felt togetherness and coordinated collaboration under comparable task conditions (Voinea et al., 2022).

Social presence can be strengthened by 3D, by offering higher levels of presence, realism, and interactivity than traditional online collaboration tools, alongside cue-rich avatar-based interaction, such as synchronous communication via text or voice, as well as additional cues including gestures, avatar appearance, and observable behaviors (van der Land et al., 2011). These affordances can support co-presence and foster communication conditions that encourage information sharing and cooperative behavior during collaborative work (van der Land et al., 2011; Yousefdeh & Oyelere, 2024). Consistent with staged accounts of social presence in metaverse interaction, embodied presence can develop into embodied co-presence through exchanges with other avatars and, through co-participation, contribute to social presence and collaborative participation (G. Zhang et al., 2022).

Integrated Conceptual Framework

This study synthesizes Self-Determination Theory, multimodal learning principles, and Embodied Social Presence Theory into a unified conceptual framework. Figure 1 shows the integrated model, in which a scaffolded multimodal metaverse environment supports DHH learners' autonomy and competence through rich, manipulable visual-spatial representations, while embodied avatar interactions

and visual communication foster relatedness. When these psychological needs are supported, higher intrinsic motivation, sustained attention, and deeper geometric understanding are anticipated. Although each component has been studied separately, the combined influence of these components on DHH learners in immersive geometry education remains empirically underexplored, constituting the primary gap addressed in this investigation.

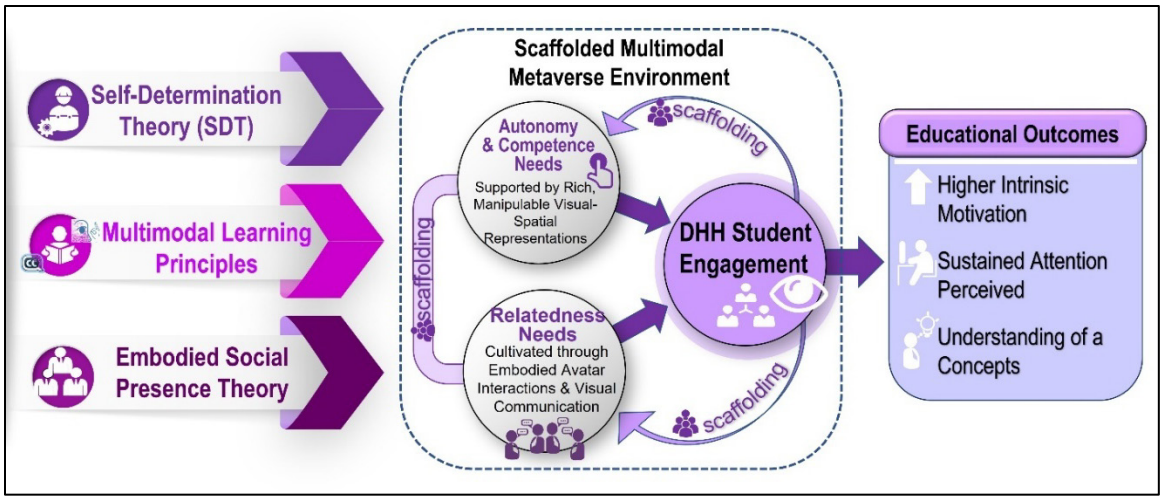

Figure 1. Conceptual framework of DHH learner engagement in a scaffolded multimodal metaverse environment

Previous Studies on Immersive and Metaverse-Based Learning

Prior research on immersive learning has assessed outcomes such as engagement, learning performance, and social interaction, but the evidence base remains uneven across technologies, learner groups, and instructional designs. Foundational measurement work established that engagement-related experiences in immersive environments can be operationalized using validated presence and user-experience instruments, including multi-scale questionnaires that explicitly capture engagement alongside presence, immersion, flow, usability, and emotion (Tcha-Tokey et al., 2016). This emphasis on measurement helps shift evaluation beyond "novelty effects" toward what learners experience and do during immersive interaction.

More recent education studies report mixed patterns. In mainstream higher education, Aziz et al. (2025) found that collaborative engagement and perceived enjoyment are key pathways associated with knowledge retention in metaverse-based learning. At the secondary level, Çelik and Baturay (2024) reported improvements in vocabulary outcomes, engagement, and perceived presence following a metaverse intervention, although gains in social presence were not statistically significant. Chang et al. (2024) similarly found that Minecraft-based metaverse instruction significantly enhanced creative design performance and learning attitudes among secondary students in a green building course. However, effects on cognitive, behavioral, and social engagement dimensions were not significant. Q. Zhang (2024) found that engagement operates alongside affective factors, including enjoyment and ambiguity tolerance, to explain learning effectiveness in metaverse-based environments.

However, evidence cautions that immersion does not automatically produce social connection or learning gains. Sadanala et al. (2024) reported weak links between engagement and learning outcomes. They noted difficulty perceiving avatars as socially real, suggesting that social presence depends on intentional pedagogical structure and interaction design. In disability-focused work, Mazhari et al. (2022) demonstrated that VR can support sign-language learning, but their evaluation focused on system and gameplay indicators rather than curriculum-based STEM learning or peer collaboration. In mathematics education, Andriyani et al. (2022) reported significant AR-related gains in

deaf students' geometry achievement, yet this line of work provides limited insight into collaborative 3D metaverse learning, social presence processes, and accessibility experiences in shared immersive environments.

Taken together, prior studies indicate that immersive and metaverse-based approaches can support engagement and learning, but the literature remains concentrated on mainstream learners, language learning, higher education, or achievement-focused AR interventions. Empirical evidence remains limited on how DHH secondary students experience engagement, visual-interactive supports, social presence, and accessibility in metaverse-based geometry learning, particularly under structured collaboration and learner-informed design principles. Table 1 summarizes key empirical studies on immersive and metaverse-based learning relevant to this study.

Table 1. Key empirical studies on immersive and metaverse-based learning

Authors	Technology	Focus and key findings	Participants	Methodology	Research gap
Çelik and Baturay (2024)	Metaverse (Spatial.io)	Reported improvements in L2 vocabulary learning, engagement, classroom community, and presence dimensions	86 mainstream secondary students (Grades 9–11)	Quasi-experimental	Did not examine DHH learners, geometry learning, or accessibility design.
Q. Zhang (2024)	Metaverse	Demonstrated that engagement and affective factors influence learning effectiveness in metaverse-based learning, underscoring the role of motivational mechanisms beyond technology alone.	University students	Quantitative survey (PLS-SEM mediation/ moderation)	Mainstream learners in a language context; did not address DHH learners or STEM learning
Andriyani et al. (2022)	Augmented Reality (Mobile AR)	Reported significant pre–post gains in deaf students' geometry achievement following AR-supported instruction.	17 deaf students	One-group pretest–posttest; paired-sample *t* test	Examined AR only; did not investigate metaverse learning, social presence, or collaboration
Mazhari et al. (2022)	VR Game (HMD-based; Oculus Quest 2)	Developed a Unity-based VR game with sign recognition for Iranian Sign Language; reported improved engagement.	5 participants	VR game development with performance-based evaluation	Focused on sign-language training; did not study geometry learning or social presence
Chang et al. (2024)	Metaverse (Minecraft)	Reported higher engagement and creative performance in a metaverse classroom compared with a non-metaverse condition.	61 secondary students	Quasi-experimental (nonequivalent groups)	Mainstream students; did not consider DHH learners or accessibility supports
Voinea et al. (2022)	Mixed Reality (Microsoft Mesh; HoloLens 2)	Found higher social presence in avatar-mediated MR collaboration compared with a video-based condition.	24 master students and professors	Experimental comparison	Focused on social presence in collaboration tasks; did not examine geometry learning or DHH accessibility

Authors	Technology	Focus and key findings	Participants	Methodology	Research gap
Sadanala et al. (2024)	Desktop VR	Reported weak engagement-outcome links and difficulty perceiving avatars as real social partners	115 students	Quantitative regression analysis	Mainstream students; did not address DHH learners or pedagogical strategies for social presence
Aziz et al. (2025)	Metaverse education	Linked immersive experiences to knowledge retention through collaborative engagement and enjoyment	453 university students	Online survey (PLS-SEM + NCA)	Higher education; did not examine DHH learners or geometry learning

Research objectives

Using an explanatory sequential mixed-methods design, the present study takes an initial step toward addressing these gaps by exploring the experiences of a small group of Malaysian DHH secondary students from one special education school when using a purposefully designed metaverse environment. Grounded in Self-Determination Theory, Multimodal Learning Principles, and Embodied Social Presence Theory, the research is guided by the following questions:

1. How do DHH students perceive their engagement in a metaverse-based geometry learning environment?
2. How do interactive visual features support DHH students' perceived understanding and interest in geometry?
3. How does social presence in the metaverse influence DHH students' peer interaction and motivation to learn geometry?
4. What accessibility supports and challenges do DHH students experience during metaverse-based geometry learning?
5. What design principles do they identify to support sustained engagement and perceived learning?

METHODS

This study employed an explanatory sequential mixed-methods design (Creswell & Plano Clark, 2017) to examine DHH students' engagement, interaction with visual and interactive features, and perceptions of social presence in metaverse-based geometry learning. The design was chosen for three reasons. First, the quantitative phase captured initial perceptions across all participants, establishing descriptive patterns to contextualize qualitative interpretation. Second, the qualitative phase provided depth and explanatory power, serving as the primary evidence source given the limited research on DHH learners in immersive virtual environments. Third, the sequential design supported purposeful selection of interview participants after the quantitative phase to maximize variation in perspectives across key learner characteristics and observed participation (Palinkas et al., 2015). This integration of breadth and depth aligns with calls for methodologically rigorous research in special education (Love et al., 2022). The design is also responsive to DHH learners' modality-specific needs, given that students must allocate attention across multiple visual information sources and that outcomes can vary widely across individuals (Marschark et al., 2005; Marschark & Spencer, 2010). Figure 2 summarizes the design from theoretical framing through intervention implementation and the two-phase data collection and analysis.

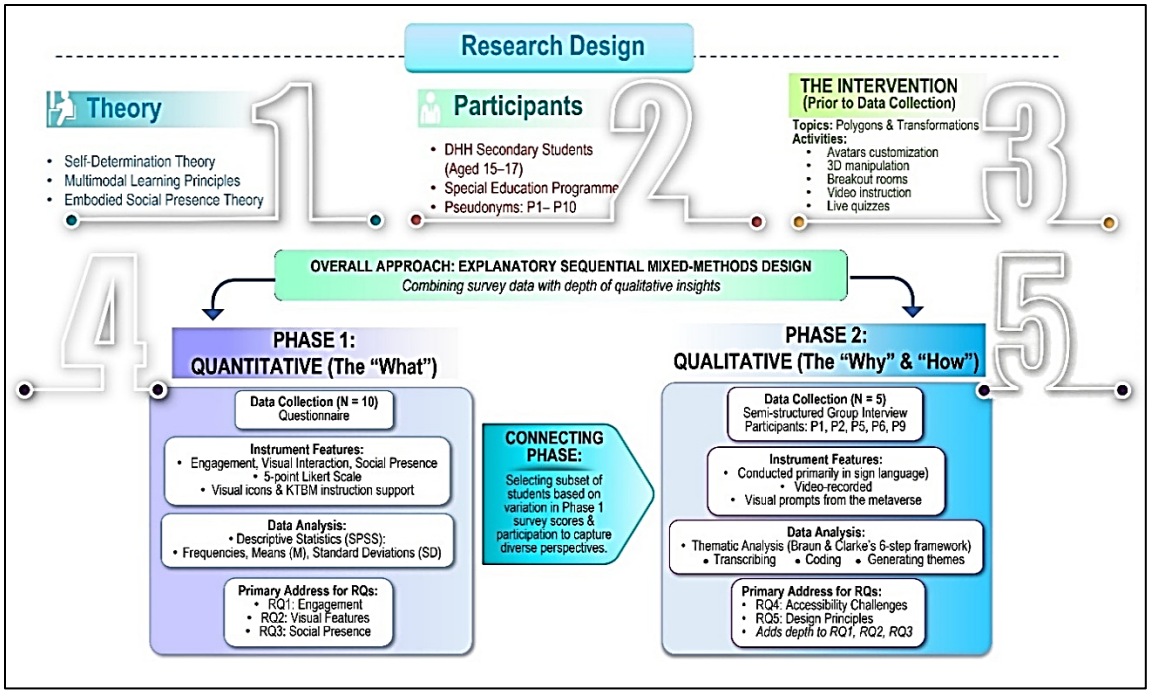

Figure 2. Overview of research design

Research Context and Setting

This study was conducted at a government secondary school with a Special Education Integration Programme (SEIP) for Deaf and Hard-of-Hearing students in Peninsular Malaysia. The SEIP is implemented in mainstream schools through dedicated special classes for students with disabilities. While students receive specialized instruction, they share the same school environment as their peers, creating opportunities for interaction and social participation within the mainstream campus (Ministry of Education Malaysia, 2015). The participating school serves approximately 30 DHH students across Forms 1-5 (grades 7-11, ages 13-17) within a larger school population of 1600 students. The DHH program is staffed by 12 certified teachers who hold bachelor's degrees in special education with a major in hearing impairment.

The metaverse-based intervention took place in the school's computer laboratory, equipped with 15 Windows-based laptops (Intel Core i5, 8GB RAM) with stable broadband internet (100 Mbps). The laboratory featured adequate lighting and minimal visual distractions, consistent with evidence that lighting conditions and visual distraction can influence DHH students' attention and academic engagement (Guardino & Antia, 2012). Students accessed the UNIVERSE by ViewSonic metaverse platform using Ministry of Education (MOE) accounts. The platform used in this study functioned as a metaverse-enabled synchronous virtual classroom that integrates avatar-based interaction with real-time instructional delivery. Students navigated the environment using customizable avatars, communicated through text-based interaction and camera use, and participated in structured learning activities within shared virtual spaces.

The platform was selected because it supported visual communication and teacher-led instruction. UNIVERSE provides interactive spaces such as classrooms and common areas and enables personalized avatar-based participation. It also offers instructional tools, including screen sharing, teacher camera presentations, and embedded quizzes, as well as options to organize learners into separate virtual spaces for small-group discussion and collaborative activities (Nguyen & Ngo, 2023). In the present intervention, these affordances supported sign-mediated instruction, structured collaboration, and multimodal geometry learning activities.

A certified deaf education teacher with 18 years of experience and fluency in KTBM delivered all instruction. The teacher completed a four-hour training session on metaverse pedagogy and platform functionality prior to the intervention. A teaching assistant provided technical support during sessions.

PARTICIPANTS

Participants were 10 DHH secondary students (6 males, 4 females) aged 15-17 years. Given the small sample, the study prioritized in-depth understanding and accessibility in data collection and interpretation rather than statistical generalization, consistent with mixed-methods special education research that uses small quantitative strands to inform qualitative explanation (Love et al., 2022). Eligibility criteria included documented bilateral hearing loss (≥35 dB), KTBM or simultaneous communication as the primary mode, no concurrent visual impairments affecting screen-based learning, basic digital literacy, and completed consent/assent procedures.

Although participants were enrolled in Forms 2-4, all had completed foundational geometry instruction covering polygons, angles, and transformations at the primary level. The metaverse-based lessons reviewed and extended these concepts rather than introducing entirely new content, ensuring a common baseline across participants. To protect confidentiality, pseudonymous codes (P1-P10) were used in all datasets and reporting. Following the quantitative phase, five students (P1, P2, P5, P6, P9) were purposefully selected for a semi-structured group interview using maximum variation sampling to capture diverse perspectives across key dimensions (Palinkas et al., 2015). Selection criteria ensured representation across key dimensions:

a. *Hearing level:* three profound, one severe, one moderate
b. *Prior metaverse experience:* three with experience, two without
c. *Classroom participation:* variation from highly vocal to reserved participants (based on teacher observation)
d. *Gender:* three females, two males

The group interview was intentionally kept small to support participation and turn-taking, consistent with mini focus group formats used when participant pools are limited (Carlsen & Glenton, 2011; Nyumba et al., 2018). The remaining five participants were not excluded due to inability or unwillingness; rather, the smaller qualitative subsample was used to enable analytic depth within available resources. Participants were also offered opportunities to review interpretations and provide feedback during member-checking procedures.

METAVERSE-BASED GEOMETRY INTERVENTION

The intervention comprised four 60-minute metaverse-based geometry lessons aligned with the Malaysian mathematics curriculum. Lesson 1 focused on platform orientation and the review of polygon properties, while Lessons 2–4 addressed key geometric transformations: translation (Lesson 2), rotation (Lesson 3), and reflection and enlargement (Lesson 4). Across all lessons, 3D manipulation enabled geometric properties and spatial relationships to be represented dynamically, allowing students to observe changes in position, orientation, and size through direct interaction with virtual objects. The instructional design drew on three theoretical frameworks: Self-Determination Theory (autonomy through customization and self-paced exploration), multimodal learning principles (visual, spatial, and kinesthetic engagement), and Embodied Social Presence Theory (avatar-mediated co-presence) (Mennecke et al., 2011; Oh et al., 2023; Ryan & Deci, 2000; Scott et al., 2023).

Lessons were structured around a combination of the following components, adapted to each lesson's objectives: platform orientation, sign-supported video instruction, guided 3D manipulation, collaborative breakout tasks, formative assessment (built-in quizzes, external quiz tools, or workbook exercises), and peer interaction through text chat and emoji reactions. Accessibility support included KTBM-integrated videos with Malay captions, persistent text chat, icon-based reaction tools, visual

alerts, and learner-controlled pacing. The lessons progressed from familiarization to guided exploration and application. A summary of the pedagogical structure, platform features, and student activities across the four lessons is presented in Table 2.

Table 2. Overview of metaverse-based geometry lessons

Lesson	Learning objective	Platform features used	Primary student activities
Lesson 1: Platform Orientation and Polygon Properties	i. To familiarize with the metaverse platform functions. ii. To review and identify polygon types based on the number of sides; recognize and describe geometric properties of triangles and quadrilaterals.	Avatar customization; navigation controls (keyboard movement); camera use; text chat; emoji reactions; screen sharing of learning materials.	Students customized avatars and practiced navigation; explored the virtual environment through guided tasks; identified and classified polygons; described properties of triangles and quadrilaterals; interacted via camera, text chat, and emoji reactions; and completed short review activities via links shared through text chat.
Lesson 2: Translation	To perform translations and identify direction and distance of movement.	3D geometric objects with drag function; text chat; emoji reactions; breakout group discussion; screen sharing, built-in live quiz.	Students explored translation by moving geometric objects to match given positions; identified direction and distance of movement; recognized that shape, size, and orientation remain unchanged; engaged in brief breakout group discussions; interacted via text chat and emoji reactions; and completed a short live quiz.
Lesson 3: Rotation	To perform rotations and identify the angle and direction of rotation.	Live manipulation of 3D geometric objects with rotation tools; guided exploration tasks; external interactive tool; screen sharing; text chat; emoji reactions; camera use; external quiz tool (Quizizz).	Students predicted the angle and direction of rotation from visual prompts; manipulated objects using rotation tools; engaged in a guided hands-on activity using an external interactive tool; compared pre- and post-rotation states; interacted via camera, text chat, and emoji reactions; and completed a short quiz.
Lesson 4: Reflection and Enlargement	i. To perform reflections across a line and identify orientation change. ii. To perform enlargements and recognize changes in size while shape remains the same.	Screen sharing of instructional videos and learning materials demonstrating reflection concepts; 3D geometric objects with drag and resize functions for exploring enlargement; text chat; and emoji reactions.	Students explored reflection and enlargement by manipulating geometric objects using drag and resize functions; identified changes in orientation and size; interacted via text chat and emoji reactions; and completed exercises in the printed module to reinforce understanding.

RESEARCH INSTRUMENTS

Questionnaire

A 22-item questionnaire measured three constructs: engagement (10 items), interaction with visual and interactive features (7 items), and perceived social presence (5 items). Responses used a 5-star scale ranging from "not at all" (1 star) to "very much" (5 stars). This format was selected to align

with a familiar star-based reporting convention (Stoyanov et al., 2015) and, given the common use of pictorial rating cues in online communication, to support an easy-to-use response process for students (Toepoel et al., 2019). Each item was accompanied by simple icons and visual cues. Instructions were provided in Malay and explained using KTBM.

Items were adapted through a structured process based on previously published instruments. Engagement items were adapted from Sadanala et al. (2024), Tcha-Tokey et al. (2016), and Q. Zhang (2024). Visual and interactive features were assessed using items adapted from established VR interactivity measures as operationalized in Yang et al. (2023). Perceived social presence items were adapted from Oh et al. (2023). To support accessibility, items were positively worded, simplified in consultation with a deaf education specialist, and accompanied by visual cues. Items were translated from English into Malay using a forward-translation procedure consistent with cross-cultural adaptation guidance (Beaton et al., 2000). Two bilingual researchers independently translated the items and resolved discrepancies through discussion.

Semi-structured group interview protocol

A semi-structured group interview protocol was developed to explore students' lived experiences in the metaverse-based geometry environment. The protocol consisted of six open-ended questions organized into thematic domains aligned with the research questions. Each question was accompanied by visual prompts (screenshots from the metaverse environment) to support recall, with follow-up probes used flexibly to elicit elaboration.

The protocol underwent two rounds of review. First, two deaf education specialists evaluated questions for linguistic accessibility, cultural appropriateness, and developmental fit, leading to simplified syntax and additional visual prompts. Second, the revised protocol was piloted with two DHH students not participating in the study, with minor adjustments made based on feedback.

Data Collection

Data collection followed the explanatory sequential mixed-methods design. Students participated in four metaverse-based geometry lessons on the UNIVERSE metaverse platform using Windows-based laptops. The first lesson embedded a familiarization phase to support initial platform use, including avatar creation, navigation within the 3D environment, and guided practice with core interaction tools (e.g., camera functions and text-based communication). Across the four lessons, instruction integrated sign-supported videos, interactive 3D model manipulation, structured breakout-room discussions, and formative assessments.

Following the intervention, all ten students completed a Malay-language questionnaire assessing engagement, interaction with visual and interactive features, and social presence. Questionnaire administration was supported through sign-language explanations and visual icons to ensure accessibility and comprehension. Subsequently, five students (P1, P2, P5, P6, and P9) were purposefully selected based on variation in questionnaire responses and observed participation for a semi-structured group interview. The 45-minute interview was conducted three days after the questionnaire in a quiet meeting room, with seating arranged in a semicircle to facilitate visual communication. The interview was conducted primarily in KTBM by a researcher fluent in sign language, with visual prompts displayed to support recall. With consent from students and guardians, the session was video-recorded to capture both signed and spoken communication.

Data Analysis

Data analysis proceeded sequentially, with quantitative analysis informing qualitative sampling and subsequent interpretation. Quantitative and qualitative findings were integrated during the interpretation phase, where qualitative themes were used to explain and contextualize quantitative patterns (Creswell & Plano Clark, 2017). Analysis was conducted using SPSS v27 for quantitative data and ATLAS.ti 24 for qualitative data management.

Quantitative data analysis

Quantitative survey data were analyzed using descriptive statistics to address RQ1 (engagement), RQ2 (interaction with visual and interactive features), and RQ3 (social presence). Given the small sample size (N = 10) and exploratory purpose of the study, inferential statistical tests were not conducted; instead, the analysis emphasized descriptive patterns within this specific group of DHH learners (Kunselman, 2024; Onwuegbuzie & Leech, 2005).

This approach is consistent with an explanatory sequential mixed-methods logic in which initial quantitative results are used to identify patterns requiring further explanation, followed by a qualitative phase designed to explain those quantitative results in greater depth (Creswell & Plano Clark, 2017). Frequencies and percentages described participant demographics and means (M). Standard deviations (SD) were calculated for engagement, interaction with visual and interactive features, and social presence. Interpretation of mean scores followed the rubric in Table 3.

Table 3. Interpretive rubric for mean values

Mean score	Level	Interpretation
1.00 – 2.33	Low	Indicates areas needing improvement and potential challenges in learning.
2.34 – 3.67	Moderate	Suggests neutral or mixed perceptions; further investigation may be required.
3.68 – 5.00	High	Indicates positive perceptions of engagement, social presence, and visual support.

Note. Mean scores were interpreted using the cut points shown to classify participants' ratings as low, moderate, or high. Items were rated on a 5-point scale from 1 (not at all) to 5 (very much). M = mean; SD = standard deviation.

Qualitative data analysis

Interview data were analyzed using reflexive thematic analysis, following Braun and Clarke's (2006) six-phase framework, which was selected for its systematic yet flexible approach to identifying patterns from DHH students' lived experiences. The analysis began with repeated reading of transcripts to achieve deep familiarity, followed by systematic coding of meaningful segments. Related codes were clustered into initial themes, reviewed, and refined against the full dataset to ensure coherence and distinctiveness. Each theme was clearly defined and named, and the final themes were woven into an analytic narrative addressing the research questions. Illustrative quotations are presented alongside each theme in the results tables (see Table 8).

Trustworthiness and Rigor

Trustworthiness was established using Lincoln and Guba's (1985) framework. Credibility was enhanced through triangulation across interview data, survey responses, and field notes, and through member checking, where all five participants confirmed that the themes reflected their experiences. Transferability was supported by providing detailed contextual information about participant characteristics, the research setting, and the analytic procedures, enabling readers to judge the relevance to other contexts. Dependability was supported through intercoder agreement, with Cohen's $\kappa = 0.73$ indicating substantial agreement (Landis & Koch, 1977) and 86.67% overall agreement. Discrepancies were discussed until consensus was reached. Confirmability was enhanced by anchoring interpretations in participants' quotations and maintaining transparency through systematic coding and theme development.

Ethical Considerations

Ethical approval was obtained from the university ethics committee and relevant educational authorities. Written parental consent and student assent were secured, with participation voluntary and students able to withdraw at any time without consequence. All data were anonymized using participant codes (P1 to P10), and no identifying information was reported. The metaverse platform and resources were provided at no cost, and the researchers had no commercial affiliation with the technology providers.

RESULTS

Participants' Demographics

This study involved ten DHH students aged 15 to 17 years. All participants were enrolled in the Special Education Integration Programme (*Program Pendidikan Khas Integrasi*, PPKI) at a national secondary school and followed the Malaysian National Curriculum (KSSM). Although a small sample size, it captured a range of hearing profiles and communication needs within the DHH population (Table 4).

Table 4. Demographic profile of respondents (N = 10)

Demographic	Frequency (f)	Percentage (%)
Gender		
Male	6	60
Female	4	40
Age		
15	2	20
16	5	50
17	3	30
Form		
Form 2	2	20
Form 3	5	50
Form 4	3	30
Hearing level		
Profound (80 to <95 dB HL)	7	70
Severe (65 to <80 dB HL)	1	10
Moderate (35 to <50 dB HL)	2	20
Assistive technology (AT)		
Hearing aids	2	20
Cochlear implant	0	0
Experience with virtual reality environments		
Roblox	8	80
Mobile Legend	3	30
Minecraft	1	10
eFooball	2	20

Note. Hearing levels followed the classification thresholds specified by Malaysia's Ministry of Health guidelines for disability registration.

Participants presented varying degrees of hearing loss. Seven had profound hearing loss (80 to <95 dB HL), one had severe hearing loss (65 to <80 dB HL), and two had moderate hearing loss (35 to <50 dB HL). Two students used hearing aids, and none had cochlear implants. In this context, students with greater residual hearing typically attend mainstream education, whereas those who rely on sign-supported communication are placed in special education. Only one participant had deaf par-

ents; the remaining nine were born to hearing parents. This mirrors widely reported population patterns in which most DHH children are born to hearing parents and therefore often experience delays in receiving accessible language input (Ritmeester et al., 2026). All participants began learning KTBM at about age seven, which corresponds to primary school entry and is later than the optimal period for early language acquisition.

Participants also reported prior experience with virtual platforms such as Roblox, Mobile Legend, Minecraft, and eFootball, indicating a basic familiarity with virtual environments that likely supported their navigation of the metaverse-based lessons. Recognizing their reliance on visual learning, the metaverse-based intervention integrated 3D models and interactive tools to support geometry learning and align with their communication needs and visual–spatial strengths.

Quantitative Analysis

Perceptions of DHH students on learning geometry in the metaverse

This subsection addresses RQ1–RQ3 by reporting DHH students' perceptions of their engagement, interaction with visual and interactive features, and social presence in the metaverse-based geometry lessons. Across the three constructs, students reported consistently high ratings. Engagement recorded the highest mean (M = 4.62, SD = 0.25), followed by social presence (M = 4.58, SD = 0.24) and interaction with visual and interactive features (M = 4.51, SD = 0.22). These results indicate very positive perceptions overall and suggest that the metaverse environment was experienced as immersive, enjoyable, and accessible for geometry learning.

Engagement

Students reported high engagement, with item means ranging from 4.10 to 4.90 (Table 5). They especially enjoyed learning new geometry concepts in the metaverse (M = 4.90, SD = 0.32) and agreed that the metaverse felt real and encouraged communication with teachers and peers (both M = 4.80, SD = 0.42). Students also reported that visual aspects of the metaverse engaged them (M = 4.70, SD = 0.48). These responses point to strong affective and behavioral engagement. The lowest mean was recorded for paying attention in metaverse-based geometry lessons (M = 4.10, SD = 0.57), suggesting that maintaining focus in a visually rich and interactive environment may be relatively more challenging for some students compared with other aspects of engagement.

Table 5. DHH students' engagement in the metaverse-based geometry lessons

Engagement with the metaverse platform	M	SD	Min	Max
1. I felt as if I were inside the metaverse	4.70	0.48	4	5
2. I felt as if the metaverse were real.	4.80	0.42	4	5
3. The visual aspect in the metaverse engages me.	4.70	0.48	4	5
4. It is easy to think about the avatars in the metaverse as real people.	4.60	0.70	3	5
5. I would be more likely to talk to teacher and friends in the metaverse.	4.80	0.42	4	5
6. I pay attention in metaverse-based geometry learning.	4.10	0.57	3	5
7. I actively participate in metaverse-based geometry learning.	4.60	0.52	4	5
8. I become so involved in the metaverse that I was not aware of things happening around me.	4.30	0.48	4	5
9. I become so involved in the metaverse that I lose all track of time.	4.70	0.48	4	5
10. I enjoy learning new things about geometry in metaverse.	4.90	0.32	4	5
Overall	**4.62**	**0.25**	**3.80**	**5**

Note. M = mean; SD = standard deviation. Scores range from 1 (not at all) to 5 (very much).

Interaction with Visual and Interactive Features

Interaction with visual and interactive features was rated highly, indicating that students generally found these elements helpful and engaging for learning geometry (Table 6). They reported that videos, camera functions, animations, and manipulating 3D objects supported their understanding (M = 4.60, SD = 0.52), while using an avatar to interact with 3D objects made learning activities easier, receiving the highest rating (M = 4.80, SD = 0.42). In contrast, the item on interactive tools helping them focus on learning showed the lowest mean (M = 4.20, SD = 0.63), suggesting that media-rich environments can still distract some students and that careful instructional design is needed to sustain cognitive focus.

Table 6. DHH students' interaction with visual and interactive in the metaverse

Interaction with visual and interactive	M	SD	Min	Max
1. Multimedia materials (e.g., videos and animations) in metaverse help me learn geometry.	4.60	0.52	4	5
2. Manipulating 3D objects in the metaverse helps me understand geometry better.	4.60	0.52	4	5
3. Using my avatar to interact with 3D objects in the metaverse makes learning activities easier.	4.80	0.42	4	5
4. The content, form, and situation in the metaverse are diverse.	4.50	0.53	4	5
5. Exploring the metaverse made me more interested in learning geometry.	4.40	0.70	3	5
6. The interactive tools in the metaverse help me focus on learning.	4.20	0.63	3	5
7. I can receive instant feedback in the metaverse.	4.50	0.53	4	5
Overall	**4.51**	**0.22**	**3.71**	**5**

Note. M = mean; SD = standard deviation. Scores range from 1 (not at all) to 5 (very much).

Social presence

Social presence in the metaverse-based geometry lessons was also rated highly by DHH students (Table 7). Overall ratings were strongly positive (overall M = 4.58, SD = 0.24), indicating that students generally experienced the environment as socially interactive rather than purely system-driven.

Table 7. DHH students' social presence in the metaverse-based geometry lessons

Social presence in metaverse	M	SD	Min	Max
1. I felt like I was in the presence of another person in metaverse.	4.10	0.57	3	5
2. I felt that the people in metaverse were aware of my presence.	4.60	0.52	4	5
3. I had a sense that I was interacting with other people in metaverse, rather than a computer simulation.	4.70	0.48	4	5
4. The people in the metaverse appeared to be sentient (conscious and alive) to me.	4.90	0.32	4	5
5. In the metaverse, I sometimes felt like I was working directly with another person.	4.60	0.52	4	5
Overall	**4.58**	**0.24**	**4**	**5**

Note. M = mean; SD = standard deviation. Scores range from 1 (not at all) to 5 (very much).

The highest endorsement was for the item "The people in the metaverse appeared to be sentient (conscious and alive) to me" (M = 4.90, SD = 0.32). Students reported feeling that they were interacting with other people rather than a computer simulation (M = 4.70, SD = 0.48). They also reported strong mutual awareness and collaborative feel, with high means for "I felt that the people in the

metaverse were aware of my presence" and "In the metaverse, I sometimes felt like I was working directly with another person" (M = 4.60, SD = 0.52). The comparatively lowest mean was recorded for the item "I felt like I was in the presence of another person in metaverse" (M = 4.10, SD = 0.57). Although this still reflects agreement, the wider spread suggests that the intensity of co-presence may have varied across students, potentially reflecting individual differences in comfort with avatar-mediated interaction or familiarity with social virtual environments.

Qualitative Findings

The follow-up group interview complements the survey results in greater depth, clarifying how and why students experienced the metaverse as engaging, visually supportive, socially meaningful, and accessible. The interview was conducted in the Malay language, supported by KTBM with five DHH students who had participated in the metaverse-based geometry lessons. Sessions were recorded and transcribed for thematic analysis. Five main themes were identified, addressing engagement (RQ1), visual-interactive learning (RQ2), social presence (RQ3), and accessibility experiences (RQ4). Design principles (RQ5) are synthesized in a separate subsection drawing across themes and survey data. Each theme includes related subthemes and illustrative quotes (Figure 2).

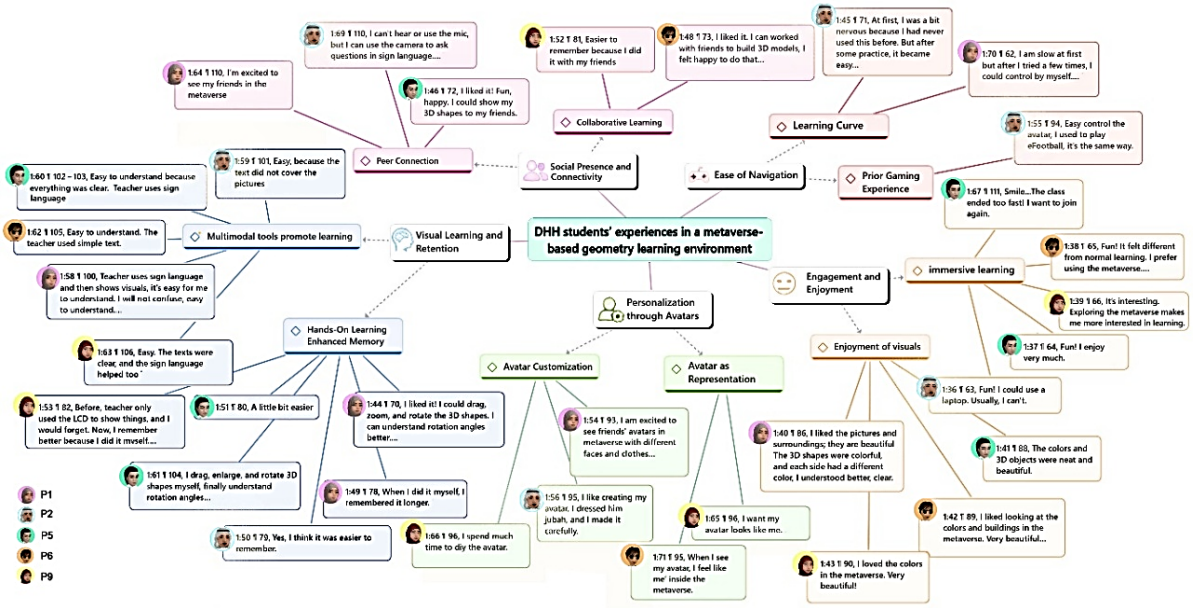

Figure 2. Themes, subthemes, and illustrative quotes from DHH students' interviews

Table 8. Qualitative themes from DHH student interviews

Theme	Subtheme	Example quotes	Supporting studies
Engagement and Enjoyment	Enjoyment of Visuals	"I liked the pictures and the metaverse environment. Everything was beautiful ..." (P1)	Adamo-Villani and Wilbur (2008); Ryan and Deci (2000)
	Immersive Learning	"Exploring the metaverse makes me more interested in learning." (P9)	Altinay et al. (2024); Mystakidis and Lympouridis (2024)
Visual Learning and Retention	Hands-On Learning Enhanced Memory	"I drag, enlarge, and rotate 3D shapes myself, finally understand rotation angles." (P5)	Al-Muqbil (2024); Aziz et al. (2025); Liu et al. (2025)

Theme	Subtheme	Example quotes	Supporting studies
	Multimodal Tools Promote Learning	"Teacher uses sign language and then shows visuals, it's easy to understand." (P1)	Scott et al. (2023); Skyer (2022)
Social Presence and Connectivity	Peer Connection	"I'm excited to see my friends in the metaverse, chatting with them." (P1)	Ghoulam and Bouikhalene (2024); Mennecke et al. (2011); Yousefdeh and Oyelere (2024)
	Collaborative Learning	"Worked with friends to build 3D models." (P6)	Fong (2023); Nagpal et al. (2023); Voinea et al. (2022)
Personalization through Avatars	Avatar Customization	"I like creating my avatar, I dressed him jubah, and I made it carefully." (P2)	Mennecke et al. (2011); K. Zhang et al. (2022, 2023)
	Avatar as Representation	"I want the avatar to look like me." (P9)	Triberti et al. (2023); Zimmermann et al. (2023)
Ease of Navigation	Prior Gaming Experience	"Easy control the avatar, I used to play eFootball, it's the same way." (P6)	Lobato-Camacho et al. (2023); Yavuz et al. (2024)
	Learning Curve	"At first, I was a bit nervous since I'd never used it, but after practice, it's easy." (P2)	Doty et al. (2025); Kley et al. (2025)

Note. Themes and subthemes were derived from interviews conducted with five DHH students (P1, P2, P5, P6, and P9) selected from the ten students who participated in metaverse-based geometry learning.

Engagement and enjoyment

The theme of engagement and enjoyment reflects students' positive emotional responses to learning geometry in the metaverse. They described the environment as attractive, interesting, and different from their usual classroom experience (Figure 3). Students highlighted the vibrant colors, 3D shapes, and virtual surroundings as features that made lessons more enjoyable than conventional methods. Statements such as "I feel like I am in another world, and it is exciting" (P2) and "Fun, it felt different from normal learning. I prefer using the metaverse" (P6) mirror the high engagement scores in the survey and indicate that the metaverse captured their attention and increased their motivation to participate in geometry lessons.

Figure 3. Students' avatars gathered in the metaverse's lobby

Note. Screenshot of students' avatars interacting in the metaverse lobby during the intervention.

Overall, the qualitative findings reinforce the quantitative results by showing that visually rich, immersive, and interactive features of the metaverse contributed to a more enjoyable and engaging learning experience for DHH students.

Visual learning and retention

This theme highlights how interactive exhibits in the metaverse supported understanding and retention of geometry concepts. Manipulating 3D shapes by rotating, dragging, and resizing them was described as both enjoyable and helpful for grasping abstract ideas (Figure 4). Although some students were initially hesitant to use the tools, practice made them feel more confident, and they found the tools easy to use. Active hands-on interaction appeared to strengthen memory for key concepts. For example, P1 noted, "When I do it myself, I can remember," while P6 explained, "Usually, I use visuals and text together." These accounts show how multimodal and interactive features in the metaverse enhanced comprehension and supported recall.

Figure 4. Students interacting with 3D geometric shapes in the metaverse

Note. Screenshot of students interacting with 3D geometric objects in the metaverse classroom.

Social presence and connectivity

The results indicate that social presence and connectivity in the metaverse are important drivers of improved collaboration and virtual interaction. For instance, breakout rooms enabled students to engage in group discussions and teamwork, thereby promoting collaborative learning (Figure 5).

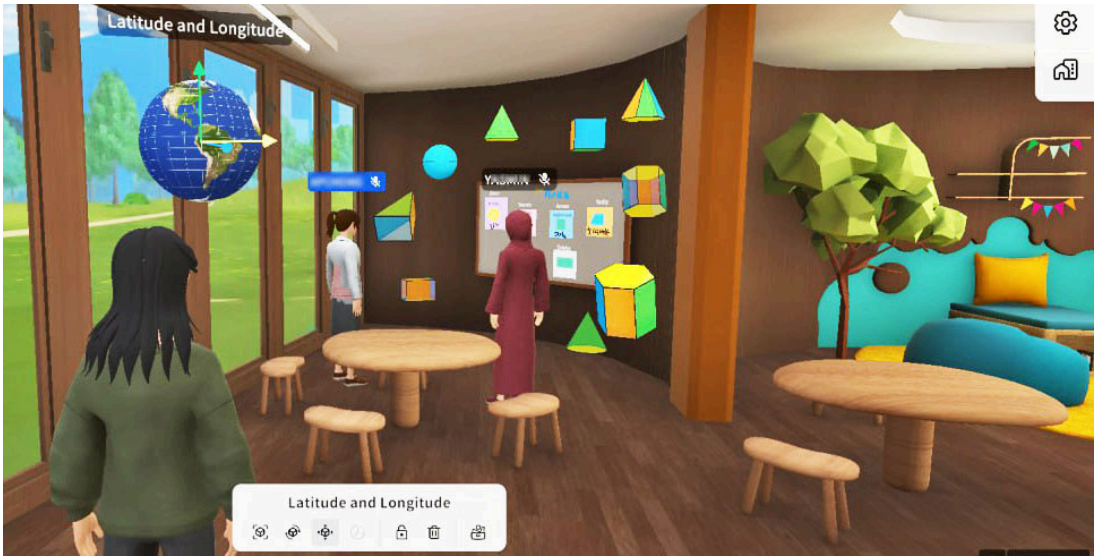

Figure 5. Students are having a group discussion in a breakout room

Note. Screenshot of a collaborative group discussion in a metaverse breakout room.

The very use of avatars enhanced students' feelings of connection with their classmates (Figure 6), as students were eager to interact in the virtual space. Some students stated: "I was excited to meet my friends in the metaverse" (P1) and "I worked with my friends to build 3D models" (P9). The finding shows that the metaverse platform not only promoted learning but also fostered an interactive social context.

Figure 6. Students expressing themselves freely in a metaverse classroom

Note. Screenshot of the metaverse environment featuring interactive notes and scaffolded support tools.

Personalization through avatars

In the metaverse, students can create their avatars by customizing features such as skin color, face, hair, and clothing (Figure 7). This level of personalization enables them to design their characters in line with who they are, fostering stronger self-confidence and encouraging constructive engagement. Avatars were particularly enjoyable for students to create, helping them feel more attached to the learning context. Students reported excitement, especially when designing their avatars and exploring different virtual areas: "I am excited to see friends' avatars in the metaverse with different faces and clothes" (P1). However, students also emphasized the need to improve avatar customization and to increase the platform's interactivity.

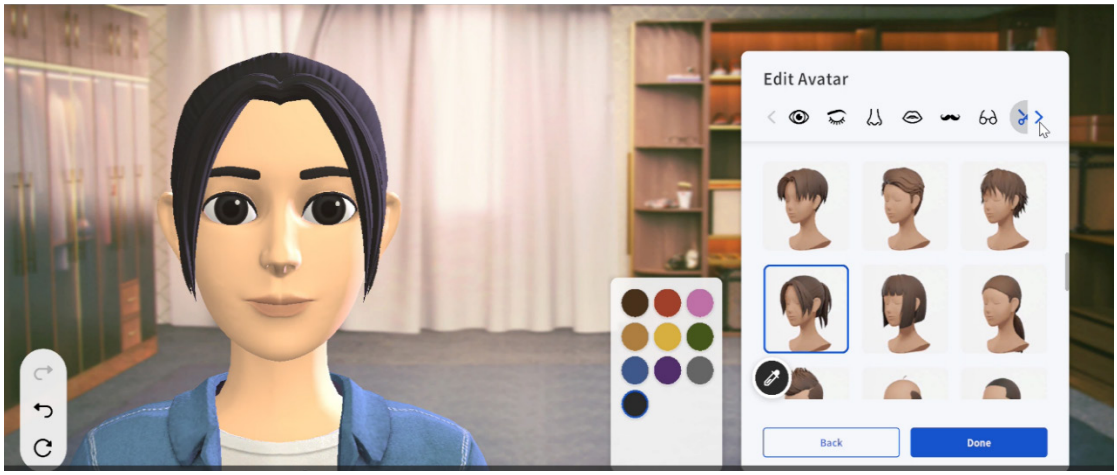

Figure 7. Customized avatars with diverse skin tones, hairstyles, and clothing

Note. Screenshot of the avatar customization interface in the metaverse platform used in the study.

Ease of navigation

Most students reported that navigating the metaverse was easy due to familiarity with its controls, similar to games like Roblox and Mobile Legends. These skills enabled students to adapt and enjoy interacting with the environment quickly. Some students stated: "I like walking my avatar around and completing tasks" (P5) and "… easy control the avatar, I used to play eFootball, it's the same way" (P6).

However, the findings also suggest areas for improvement, such as enhancing accessibility with features like camera support for sign language and refining interactive tools to address initial learning challenges better. These insights demonstrate the potential of the metaverse as a transformative educational tool for DHH students, offering a platform that supports academic learning while also promoting social inclusion and meaningful engagement.

Additional feedback further illustrated students' enjoyment of the metaverse experience. For example, P2 remarked, "I could not use the mic, so I turned on the camera to ask the teacher questions". Another student, P1, said, "I want more classes like this", and P5 noted, "This opened my eyes, I never knew about the metaverse before". These responses demonstrate students' strong interest in using the metaverse platform for future lessons, reflecting its potential to enhance both learning and engagement.

Instructional design principles

Drawing on interview themes and survey feedback, student feedback identifies several instructional principles for metaverse-based geometry lessons. Students consistently preferred multimodal explanations with clear visuals, which align with high ratings for the visual aspects of the metaverse (M = 4.70) and perceived realism (M = 4.80). As one student explained, "Teacher uses sign language and then shows visuals, it's easy for me to understand … I will not confuse" (P1), while another highlighted the importance of clear 3D visualization, noting, "I could see the whole 3D shape clearly" (P2).

Besides that, students also emphasized hands-on manipulation of 3D objects as key to understanding and memory, consistent with strong ratings for manipulating 3D objects (M = 4.60). They described using actions such as dragging, zooming, and rotating to grasp rotation angles. They linked learning gains to active doing, for example: "Now, I remember better because I did it myself" (P9). Peer-supported collaboration emerged as another valued element, reflecting high social presence overall (M = 4.58). Students shared that "I could show my 3D shapes to my friends" (P5) and "worked with friends to build 3D models" (P6).

Students further stressed the need for accessible communication options aligned with DHH preferences, reflected in strong endorsement of avatar-mediated involvement (M = 4.80). They also noted practical constraints in audio-based tools: "I can't hear or use the mic, but I can use the camera to ask questions in sign language" (P2). Together, these findings suggest that metaverse lessons for DHH learners should prioritize visual clarity, manipulable 3D learning-by-doing, structured peer interaction, and accessible communication supports, alongside sufficient guidance to help sustain attention and maintain focus when using interactive tools.

DISCUSSION

This study examined how deaf and hard-of-hearing (DHH) students experienced an immersive, metaverse-based geometry lesson. Integrating quantitative survey data with qualitative interview accounts, the findings suggest that the environment was associated with high engagement, positive perceptions of visual and interactive learning tools, and a strong sense of social presence. However, lower ratings for sustained attention and tool-supported focus indicate that some learners found the media-rich environment demanding. In the sections that follow, these findings are interpreted with

reference to relevant theory and prior research, alternative explanations are considered, and implications for design, practice, and future inquiry are discussed.

Engagement in Metaverse-Based Environment

Students reported high engagement, including strong enjoyment, realism, and motivation, which was reinforced by interview descriptions of the environment as "exciting," "different from normal learning," and preferable to conventional lessons. These findings align with recent metaverse studies that report heightened interest, participation, and enjoyment when learners explore visually rich, interactive learning environments (Al-kfairy et al., 2024; Bali et al., 2024; Çelik & Baturay, 2024; Muthmainnah et al., 2023; Sadanala et al., 2024). For DHH learners who benefit from visual and concrete supports for abstract geometry, immersive 3D environments may provide a more accessible entry point through interactive spatial exploration rather than text-heavy representations (Andriyani et al., 2022; Domínguez Vázquez & Díaz Palencia, 2024; Yazdi, 2025).

From a Self-Determination Theory perspective, this engagement profile reflects conditions supporting autonomy, competence, and relatedness (Deci & Ryan, 2008). Students described self-paced exploration and avatar control, suggesting perceived agency consistent with research linking user control to motivation in immersive contexts (Gim et al., 2023; Ibrahim et al., 2025). Notably, students expressed a desire to "join again," which may suggest that engagement was not solely driven by initial exposure to the environment, although this interpretation remains tentative.

A key consideration concerns whether the observed engagement reflects enduring pedagogical value or short-term increases in motivation associated with initial exposure to a novel learning environment. While immersive and game-like features are effective in stimulating interest and participation, research suggests that these effects do not necessarily translate into improved conceptual understanding or sustained learning outcomes (Papadakis & Karakose, 2025). Given the brief duration of the intervention, the present study cannot determine whether engagement would persist over time. Longitudinal research is therefore needed to distinguish between initial enthusiasm and more stable patterns of motivation as learners become familiar with metaverse-based instruction (Miguel-Alonso et al., 2024; L. Rodrigues et al., 2022).

Visual and Interactive Features for Understanding and Interest

High ratings for interaction with visual and interactive features, together with interview themes on visual learning and retention, indicate that multimodal tools played a central role in how students made sense of geometry in the metaverse. Students described manipulating 3D objects, rotating shapes, and viewing animations as helpful for grasping angles, faces, and spatial relationships, while sign-supported explanations and clear text reduced confusion. This aligns with research demonstrating that interactive visualizations support comprehension of abstract concepts through manipulable, spatially enriched representations (Medina Herrera et al., 2024; Siregar, 2025).

For DHH students in particular, these findings converge with evidence that visually rich and interactive environments enhance mathematical understanding and motivation by capitalizing on visual–spatial strengths (Aboud & Al Ali, 2025; Andriyani et al., 2022; Topraklıkoğlu & Öztürk, 2025). Students' reports that 3D manipulation made geometry more tangible align with research suggesting interactive 3D environments support spatial processing more effectively than 2D displays (da Silva Soares et al., 2024; Han et al., 2025). Additionally, prior work highlights the accessibility potential of immersive systems that incorporate sign language through avatar-based signing and other visual communication supports for deaf learners (Alam et al., 2024; Berrezueta-Guzman et al., 2025; Shao et al., 2020; Wiliyanto et al., 2025).

At the same time, it is important to separate perceived learning from demonstrated learning. The present study examined students' experiences and perceived helpfulness of interactive features rather

than achievement gains. Prior research shows that learners' perceived learning can diverge from objective learning and may even be negatively related under certain instructional conditions (Deslauriers et al., 2019). Therefore, while students valued the interactive features and viewed them as supportive, future studies should verify their instructional impact using achievement-focused designs, such as pre–post geometry measures, performance-based spatial tasks, or comparative conditions that isolate specific feature contributions.

Social Presence and Collaboration

Students reported a strong sense of social presence, frequently describing interactions as occurring with "real people" rather than a computer simulation. These patterns support the interpretation that the metaverse lessons successfully produced co-presence and mutual awareness, with students also reporting that others were aware of their presence and that they sometimes felt they were working directly with another person. In immersive virtual environments, presence is commonly conceptualized to include social presence in collaborative virtual environments, with engagement treated as a related component of user experience (Tcha-Tokey et al., 2016). These experiences align with Embodied Social Presence Theory, which emphasizes avatar embodiment, shared space, and multimodal communication as foundations for co-presence and identity expression in virtual environments (Mennecke et al., 2011). The findings are also consistent with the Community of Inquiry framework's emphasis on social presence as support for trust and participation in online learning (Garrison et al., 1999).

Although the co-presence item showed the lowest mean, it still reflected agreement. It may indicate that the intensity of "being with" others varied across individuals, potentially influenced by differences in familiarity with avatar-mediated social spaces. However, evidence suggests that social presence is not an automatic outcome of immersive technology. For example, some studies report high engagement without significant gains in social presence, indicating that design and pedagogical structure play a critical role (Çelik & Baturay, 2024). The present findings support this conditional interpretation: peer connection appeared to be most evident when learners were provided with structured group activities, breakout rooms, and shared construction tasks rather than unstructured exploration. This aligns with Ghoulam and Bouikhalene's (2024) emphasis on purposeful small-group structures and with social presence scholarship that conceptualizes presence as a felt sense of "being together" with others (Nowak & Biocca, 2003).

Avatar-mediated identity and participation

Avatars appeared to support self-expression and participation. Students described experiencing their avatars as extensions of themselves, consistent with research showing that virtual worlds enable users to project and extend their identities through avatar design (Jande & Ibrahim, 2020; Zimmermann et al., 2023). The qualitative interviews indicate that avatars played an important role in students' participation and sense of connection. Students reported enjoyment and interest in seeing classmates' avatars and interacting in shared virtual spaces. This suggests that avatar design and visibility may have supported participation by making peers more socially salient and by reinforcing the feeling that others inhabited the space. In this way, avatar presence appeared to support participation by making peers more perceptually and socially present to one another.

At the same time, students' feedback on improving avatar customization and increasing interactive features points to design opportunities to strengthen social accessibility and sustain collaboration. These qualitative patterns are consistent with prior work demonstrating that avatar customization is shaped by social context and supports identity projection and self-presentation processes in virtual environments (Kang & Kim, 2020; Wu et al., 2023). In addition, research on avatar design in virtual education indicates that well-designed customization systems can enhance user engagement, with implications for participation in immersive learning settings (Tinmaz & Singh Dhillon, 2024).

For users with disabilities, avatars may function as channels for strategic identity disclosure. K. Zhang et al. (2023) demonstrated that users with disabilities can selectively disclose or withhold disability-related information through avatar features as part of self-presentation and risk management. However, this study did not examine whether DHH students used avatar customization to express or conceal their deaf identity. Future research should therefore explore how avatar design choices intersect with identity expression, disclosure strategies, and social participation among DHH learners in immersive educational environments.

Accessibility, Attention, and Cognitive Load

Although students' overall perceptions were highly positive, the lowest survey ratings concerned sustaining attention and whether interactive tools helped maintain focus. Interview comments about initial nervousness and managing multiple tools suggest that some learners found the environment cognitively demanding. This pattern aligns with evidence that immersive environments can heighten engagement while simultaneously increasing the risk of cognitive overload when information is dense or poorly coordinated (Graf & Antoni, 2021; Sadanala et al., 2024; Sari et al., 2023).

Notably, students reported that familiarity with gaming interfaces such as Roblox and Mobile Legend supported their adaptation to the metaverse platform. While prior gaming experience may reduce the learning curve, educators should not assume all DHH students share this advantage, and explicit orientation remains essential.

For DHH students, cognitive load challenges are amplified because vision serves as the primary channel for both language access and learning. They often divide visual attention across teachers, interpreters, captions, and instructional materials, leading to fragmented processing and increased demands on working memory (Bavelier et al., 2006; Luft & Brochu, 2023; Marschark et al., 2006). Sustained split attention elevates extraneous cognitive load and can undermine comprehension, consistent with cognitive load theory and split-attention effects (Ayres & Sweller, 2014; Mather & Clark, 2012). Reviews of immersive learning similarly caution that poorly coordinated visual streams increase cognitive strain rather than learning benefits (Mystakidis & Lympouridis, 2024).

The comparatively lower rating for sustained attention ($M = 4.10$), therefore, reflects not a contradiction of the conceptual framework but a boundary condition of immersive multimodal learning. While visually rich environments support engagement, they may also impose competing attentional demands when multiple visual streams are presented simultaneously. In this context, multimodal richness supports learning only when visual information is carefully sequenced and coordinated rather than concurrently presented, consistent with principles of cognitive load management and structured multimedia design (Ayres & Sweller, 2014; Mather & Clark, 2012).

These findings highlight the importance of deliberate instructional orchestration in metaverse-based learning environments. Effective design should minimize unnecessary visual switching by aligning sign language, captions, and instructional visuals within a coherent spatial layout, while sequencing tasks progressively and limiting the number of concurrent interactive elements (Gehret & Elliot, 2025; Luft & Brochu, 2023; F. M. Rodrigues et al., 2022). This aligns with immersive-learning syntheses that emphasize personalization and accessibility, reduced cognitive effort, and scaffolded support as central practices for managing learners' cognitive demands (Beck et al., 2024).

Design priorities emerging from learner experience

Students' feedback suggests that effective metaverse geometry lessons depend less on novelty and more on coordinated scaffolding. They prioritized visually clear, multimodal explanations that integrate sign-supported instruction with concise text and manipulable 3D models. This aligns with deaf education scholarship emphasizing coordinated multimodal resources to support access and learning (Scott et al., 2023; Skyer, 2022) and with recommendations to minimize split visual attention for DHH learners (Luft & Brochu, 2023). Students also valued hands-on 3D manipulation, indicating

that interactivity should be treated as a core instructional mechanism rather than an optional feature (Andriyani et al., 2022; Domínguez Vázquez & Díaz Palencia, 2024).

Students further emphasized structured collaboration and usability, preferring guided small-group tasks such as breakout discussions and shared construction activities. This aligns with evidence that collaborative virtual spaces are most effective when tasks are structured and supports are explicit (Laine & Lee, 2024). Overall, these findings position accessibility as an instructional design requirement, calling for coherent visual layouts, paced interaction, and scaffolded tasks that sustain engagement while remaining cognitively manageable.

Contribution to the Literature

This study extends metaverse-based learning research for DHH students by examining how multimodal representations, avatar-mediated social presence, and motivation-related processes described in Self-Determination Theory may operate together in an immersive geometry lesson (Deci & Ryan, 2008). While prior work has documented DHH learners' reliance on visual-spatial processing in conventional and online settings, research on metaverse-based mathematics learning and avatar interaction in special education remains limited (Blatto-Vallee et al., 2007; Luft & Brochu, 2023; Tanrıdiler, 2024).

The findings offer preliminary evidence that metaverse participation may support both affective engagement and social connection for DHH learners. The association between avatar-related features and social presence suggests that embodiment in a shared virtual space could help DHH learners feel visible, connected, and able to collaborate, extending prior work on behavioral interdependence and avatar-mediated interaction (Mennecke et al., 2011; Voinea et al., 2022) and aligning with evidence that multiuser metaverse spaces can strengthen participation for DHH learners (Mystakidis et al., 2024).

From a theoretical standpoint, this study suggests refinement of how SDT and Embodied Social Presence Theory are applied in inclusive digital learning contexts. The findings indicate that autonomy, competence, and relatedness may be supported simultaneously through visual-spatial interaction and avatar embodiment, but these benefits appear contingent on an accessible design that manages cognitive load. The contribution lies in highlighting boundary conditions under which such support may occur for learners with specific accessibility needs. Future theoretical work should integrate accessibility constraints into frameworks for immersive learning, recognizing that features enhancing engagement for some learners may create barriers for others.

Implications

Implications for design and educational practice

For designers and educators, the findings point to three interrelated priorities. First, accessibility should be embedded from the outset rather than retrofitted. Visual materials, captions, and sign-supported explanations need to be spatially coordinated and clearly structured to reduce split attention and manage cognitive load. Second, interactive features such as 3D objects and avatars should serve clear pedagogical purposes: manipulable models should make abstract geometric ideas tangible, and avatars should support communication and identity expression rather than function as decoration. Third, collaborative tools should be intentionally structured, with explicit task guidance and manageable group sizes, as peer interaction appears most beneficial when scaffolded rather than left to emerge spontaneously.

For teachers working with DHH students, the results suggest that metaverse-based learning may be a valuable complement to classroom instruction, particularly for visually demanding subjects such as geometry. However, successful implementation requires careful planning. Teachers should provide explicit guidance, model navigation strategies, and introduce tools gradually to prevent cognitive overload. Professional development is essential to help educators design inclusive lessons, manage immersive learning environments, and troubleshoot accessibility challenges. Without such support,

the benefits of metaverse-based instruction may not be realized, and the technology could inadvertently create new barriers.

Although the present study focused specifically on DHH learners, the design principles emerging from this work align with the broader framework of Universal Design for Learning (UDL), which advocates for multiple means of representation, action, and expression, and engagement to reduce barriers across diverse learner populations (CAST, 2024). The visual-gestural affordances developed for this intervention, including coordinated multimodal input, manipulable 3D representations, captioned sign-supported instruction, and avatar-mediated communication, address accessibility needs that extend beyond the DHH population. Students learning in a second language, learners with low spatial reasoning ability, and students who benefit from embodied interaction may similarly gain from environments that prioritize visual clarity, paced scaffolding, and structured peer collaboration over text-heavy or lecture-dependent formats. This alignment suggests a curb-cut dynamic in which designing for specific accessibility needs produces learning environments that are more effective for all. Framing the present findings through UDL positions metaverse-based accessible design not as a narrow special education concern but as a contribution to inclusive instructional design in immersive learning environments more broadly.

Implications for research

For researchers, this study points to several priorities for advancing the field. First, future work should incorporate comparison conditions to determine whether benefits attributed to metaverse environments are specific to immersive three-dimensional platforms or could also arise from other well-designed instructional approaches. Second, longitudinal designs are needed to examine whether engagement and learning outcomes are sustained over time and to distinguish pedagogical effects from novelty influences. Third, achievement-based measures should be included alongside experiential data to determine whether positive perceptions are accompanied by measurable learning gains. Finally, researchers should investigate individual differences, such as prior technology experience, working memory capacity, and communication preferences, that may shape how DHH learners engage with and benefit from metaverse-based instruction.

Limitations And Future Research

This study has several limitations. First, the small sample cannot capture the full diversity of DHH students; future studies should recruit larger, more diverse cohorts across multiple schools. Second, the brief intervention (four lessons) precludes claims about sustained engagement or learning gains; findings reflect initial perceptions and may partly reflect novelty effects. Third, without a formal baseline assessment, no claims are made about learning gains; findings are best interpreted as evidence about engagement, feature interaction, and perceived social presence. Fourth, the study did not isolate how avatar customization shapes motivation, identity, or learning; experimental designs manipulating avatar options would be informative.

Future research should adopt longitudinal approaches to examine whether observed experiences translate into sustained benefits, including achievement, self-efficacy, and social-emotional outcomes. Researchers should also evaluate advanced accessibility supports, including AI-supported signing avatars, gesture recognition, and adaptive captioning, through interdisciplinary collaborations across educational technology and DHH education.

Conclusions

Metaverse-enabled 3D environments show promise for engaging and inclusive geometry learning for DHH students. In this study, immersive visuals, manipulable 3D representations, and avatar-mediated participation were associated with high engagement, positive interaction with learning tools, and

strong social presence. Students' reflections indicated that direct manipulation of 3D objects supported their perceived understanding and that peer interaction strengthened motivation and collaborative participation.

At the same time, comparatively lower ratings related to sustained attention and tool-supported focus suggest that some students experienced difficulty managing a media-rich environment. This finding highlights the importance of careful instructional orchestration to reduce split visual attention and manage cognitive load, particularly for DHH students who rely heavily on visual channels for both task information and communication. The practical implication is the need for structured pedagogical guidance on how teachers can sequence activities, scaffold interaction, and integrate accessibility supports so that metaverse-based instruction remains effective and sustainable in real classrooms.

Overall, this study offers early evidence that metaverse-based lessons can support inclusive geometry learning for DHH students. With accessibility-aware design and structured teaching practices, metaverse-based learning can contribute to both perceived understanding and social inclusion for DHH learners.

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