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Signs, Shapes, and Spaces: A CAMIL-Informed Qualitative Study of Metaverse Geometry Learning for Deaf and Hard-of-Hearing Students

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Abstract

Deaf and Hard-of-Hearing (DHH) students face persistent barriers in geometry education due to instructional approaches that inadequately support visual communication and embodied learning. This study examined DHH students' experiences with GeoMETriA, a metaverse-based geometry learning platform integrating sign language instruction, three-dimensional visualization, and avatar-mediated interaction. Guided by the Cognitive Affective Model of Immersive Learning (CAMIL), a multi-phase qualitative design was employed, including pre-workshop interviews with four special education teachers and post-workshop focus group discussions with seven DHH secondary students following a four-session learning workshop. The findings indicate that gamified activities and peer collaboration enhanced interest and sustained engagement, while avatar customization supported embodiment and a sense of presence. Students described progression from initial uncertainty to greater confidence through practice and scaffolded support. However, cognitive and usability challenges emerged, particularly concerning sign language video pacing, navigation complexity, and limited instructional scaffolding. The study contributes theoretically by extending CAMIL-informed interpretations to sign-supported metaverse learning, empirically by documenting how engagement, embodiment, and self-efficacy develop during immersive geometry learning, and practically by offering design implications including adjustable sign language delivery, structured scaffolding, and culturally responsive avatar options. These findings suggest that metaverse-based platforms hold promise for supporting DHH learners when accessibility and learner-centered principles are embedded as foundational design considerations.

Keywords: accessibility; deaf and hard-of-hearing (DHH); metaverse; CAMIL; geometry; special education; immersive technology; visual-spatial learning

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1. Introduction

Access to equitable and meaningful education remains a persistent social challenge for Deaf and Hard-of-Hearing students, particularly in disciplines that rely heavily on abstract reasoning and spatial visualization, such as geometry (Husniati et al. 2020). The term Deaf and Hard-of-Hearing (DHH) is used as an inclusive descriptor for learners with varying degrees of hearing loss and communication modalities, while recognizing

that deafness may be understood not only as an audiological condition but also, for some learners, as a cultural and linguistic identity (Knoors and Marschark 2014). Central to this discussion is the concept of access, which refers to learners' ability to perceive, understand, and meaningfully participate in instructional communication and learning activities (Mayer and Trezek 2023; Knoors and Marschark 2014). Although global commitments to inclusive education have expanded in recent decades, DHH learners continue to face structural barriers rooted in hearing-centric instructional norms, communication practices, and digital infrastructures that privilege spoken language and auditory input (Aljedaani et al. 2023; Lillo-Martin et al. 2023; Silvestri and Hartman 2022). These barriers carry consequences that extend beyond academic difficulty alone. They reflect deeper concerns of participation, agency, and social inclusion, as DHH students frequently encounter learning environments that fail to accommodate the visual communication and embodied modes of interaction essential to how they learn (Eichengreen et al. 2025; Schwab et al. 2019).

The urgency of accessible learning design is further reinforced by global and national trends. Globally, more than 34 million children live with disabling hearing loss, highlighting the need for accessible educational environments and communication support during schooling (World Health Organization 2021). Projections further indicate that by 2050, an estimated 2.5 billion people worldwide may experience some degree of hearing loss, with approximately 700 million requiring hearing rehabilitation services (World Health Organization 2021). In Malaysia, disability registration records indicate over 48,000 individuals classified under hearing disability, including more than 5600 children and adolescents (Ministry of Women Family and Community Development 2025). While registration figures do not reflect prevalence, they signal increasing demand for instructional approaches that systematically address accessibility in formal education. Meeting this demand requires not only policy commitment but also pedagogical and technological innovation that places accessibility at the core of learning design.

In response to these challenges, digital technologies have increasingly reshaped how education is organized, delivered, and experienced. Learning has progressively shifted toward interactive, learner-centered, and experience-based approaches that emphasize active participation rather than passive knowledge transmission (Timotheou et al. 2022; Yang et al. 2025). Within this evolving landscape, the metaverse has gained attention as a networked ecosystem of immersive environments that blend virtual reality (VR), augmented reality (AR), and interactive digital media to support real-time participation and collaborative learning (Chamola et al. 2025; Kaddoura and Al Husseiny 2023; Park and Kim 2022). Beyond its popular association with entertainment, the metaverse is increasingly understood as a space capable of facilitating collaboration, presence, and learner-centered pedagogical practices across geographical boundaries (Koohang et al. 2023; Onu et al. 2024).

More recently, scholarly attention has begun to shift toward the potential of the metaverse to support students with diverse abilities (Altinay et al. 2024; Di Dario et al. 2024). Nevertheless, most existing platforms and empirical studies remain oriented toward hearing populations, with accessibility features often implemented as supplementary adaptations rather than foundational design principles (Creed et al. 2024; Dudley et al. 2023; Othman et al. 2024). As a result, limited empirical understanding exists regarding how metaverse environments designed from the outset to address the learning and communication needs of DHH students, rather than adapted retrospectively, can support the cognitive, affective, and social dimensions of learning. This gap is particularly important in mathematics contexts, where spatial reasoning and conceptual understanding are central (Creed et al. 2024; Dudley et al. 2023; Thom and Hallenbeck 2021).

1.1. Geometry Learning Challenges for DHH Students

Geometry presents distinctive challenges for DHH learners because it demands symbolic interpretation, spatial reasoning, and abstract visualization (Thom and Hallenbeck 2021, 2022). Although DHH students often rely on visual and spatial information, researchers caution against assuming uniform visual-spatial advantages across this population (Marschark et al. 2015a; Marschark et al. 2017). Evidence suggests that differences in representational strategies can contribute to gaps in conceptual problem solving, with deaf learners more likely to retain pictorial representations that do not fully capture relational structures underlying geometric concepts (Blatto-Vallee et al. 2007). These difficulties stem not from inherent deficits but from instructional designs poorly aligned with DHH students' multimodal learning needs (Knoors 2016; Knoors and Marschark 2014; Marschark et al. 2015b).

Conventional geometry instruction compounds these misalignments by relying on verbally mediated explanations and static representations that limit opportunities for dynamic spatial visualization (Sinclair and Bruce 2015; Thom and Hallenbeck 2022). While instruction for DHH students may involve combinations of spoken, signed, and text-based supports (Marschark et al. 2006; Scott et al. 2023; Skyer 2023), such approaches do not always support the development of spatial thinking essential for geometric reasoning (Krause and Wille 2021; Zhu et al. 2023). As a result, DHH students may experience delayed comprehension and reduced problem-solving performance in geometry-related tasks (Blatto-Vallee et al. 2007; Cawthon et al. 2022; Gottardis et al. 2011).

These challenges are further shaped by disparities in early language access. More than 90% of DHH children are born to hearing parents, and many therefore experience delayed access to language, particularly when early sign language exposure is limited (Mitchell and Karchmer 2004; Shusterman et al. 2022). Although sign language is essential for classroom access and conceptual communication in mathematics (Henner et al. 2021; Kurz and Pagliaro 2019), abstract geometric reasoning requires learners to coordinate multiple representational forms, including diagrams, symbolic notation, and visualizations, to interpret complex spatial relationships (Arcavi 2003; Duval 2006; Thom and Hallenbeck 2021).

For DHH learners, mathematical understanding therefore depends on connections between spatially organized sign language, mathematical notation, and conceptual representations (Kurz and Pagliaro 2019). When early language access is limited, learners may encounter additional difficulties coordinating these representations and developing relational understanding of geometric concepts (Santos and Cordes 2022). Consequently, foundational gaps associated with early language deprivation may persist into secondary education, where abstract geometric reasoning becomes increasingly central (Pagliaro and Ansell 2012; Schindler et al. 2022; Walker et al. 2023).

The heterogeneity of the DHH population further intensifies these challenges. Between 40 and 65 percent of DHH students present with comorbid disabilities, including speech impairments and cognitive processing difficulties (Bowen and Probst 2023; Peterson et al. 2023). Yet many instructional materials lack dynamic visualizations, structured scaffolding, and responsive feedback, contributing to cognitively passive and socially isolating learning environments (Tanrıdiler 2024). Consequently, many learners require extended processing time and visually explicit representations to construct geometric understanding (Andriyani et al. 2022; Gremp et al. 2019; Gürefe 2022).

1.2. Immersive Technologies as a Response to DHH Learning Needs

A growing body of research underscores the importance of visual and spatial representations in geometry instruction for DHH students, who frequently rely on schematic visualization and spatial reasoning to interpret geometric relationships (Abylkassymova

et al. 2025; Andriyani et al. 2022; Thom and Hallenbeck 2021). Instructional approaches prioritizing interactive visualization, spatial manipulation, and visual feedback align with DHH learners' multimodal needs given limited auditory access (Abdullah Almulhim et al. 2025; Olszak and Borowicz 2025). While the notion of inherent visual-spatial cognitive advantages among DHH populations has been challenged (Marschark et al. 2017; Rodrigues et al. 2022b), research on embodied cognition suggests that spatial reasoning tasks in geometry offer productive pedagogical entry points that leverage multimodal engagement rather than auditory dependency (Thom and Hallenbeck 2021, 2022).

Building on these insights, immersive technologies have increasingly been explored as a response to persistent instructional challenges in geometry learning for DHH students (Andriyani et al. 2022; de Oliveira et al. 2022). These environments enable learners to interact with three-dimensional representations, explore spatial relationships dynamically, and engage in collaborative problem solving (Chen et al. 2024; Su et al. 2022; Walkington et al. 2024). When intentionally designed, immersive platforms have been associated with deeper conceptual engagement, enhanced motivation, and improved spatial understanding (Christopoulos et al. 2024; Tene et al. 2024). Importantly, such environments reduce reliance on language-intensive formats by prioritizing visual interaction, spatial movement, and object manipulation (Aboud and Al Ali 2025; Andriyani et al. 2022; Fernandes et al. 2024).

Beyond individual interaction with content, immersive technologies also create new opportunities for social learning. Avatar-mediated communication and shared virtual spaces allow learners to collaborate, observe peers, and engage in joint problem solving in real time (Teng et al. 2023; Yousefdeh and Oyelere 2024). These visually mediated forms of social interaction are particularly consequential for DHH learners because participation in signed and multimodal classrooms depends on coordinating joint visual attention (e.g., gaze shifting) across interlocutors and task objects, with both teachers and peers serving as key interaction partners rather than relying primarily on auditory access (Lieberman et al. 2013; Marschark and Spencer 2010; Singleton and Crume 2022).

Despite these promising affordances, many immersive platforms remain insufficiently accessible, including limited integration of sign language support, flexible captioning, and visual scaffolding needed for meaningful participation (Creed et al. 2024; Dudley et al. 2023). Consistent with these concerns, research on digital learning for deaf students highlights persistent accessibility barriers, including inadequate sign language availability and related inequities in participation (Aljedaani et al. 2023; Gehret and Elliot 2025).

Taken together, these findings indicate that while immersive technologies hold considerable potential for DHH learners, their effectiveness depends on accessibility-centered design. A clear need exists for immersive learning environments that coherently integrate visual–spatial interaction, social collaboration, and accessible communication supports within a theoretically informed framework. Addressing this gap requires both technological innovation and conceptual models capable of explaining how immersive experiences shape cognitive, affective, and social dimensions of learning for DHH students.

1.3. Theoretical Framework: Cognitive Affective Model of Immersive Learning

To address this gap, the present study adopts the Cognitive Affective Model of Immersive Learning (CAMIL) as an analytical lens for examining DHH students' experiences of geometry learning within a metaverse-based environment. CAMIL provides a comprehensive framework for understanding how immersive learning experiences influence engagement and learning outcomes through interrelated psychological and cognitive processes (Makransky and Petersen 2021). Rather than focusing solely on technological features, CAMIL explains how immersive environments shape learning through psychological affordances, particularly presence and agency, which influence affective and cognitive

processes associated with learning outcomes. Although Universal Design for Learning (UDL) provides valuable principles for accessible curriculum design (CAST 2018), CAMIL was selected because it offers an analytical framework for examining how immersive learning environments shape learners' cognitive, affective, and social experiences, which aligns more directly with the experiential focus of the present study.

CAMIL has been widely applied in studies of virtual reality and immersive learning in mainstream educational contexts (Bartels and Hahne 2023; Jiang et al. 2025; Rassy et al. 2023), but its application to DHH learners in sign-supported, metaverse-based environments remains underexplored. Although the CAMIL was originally developed to explain learning processes in immersive virtual reality environments (Makransky and Petersen 2021), empirical research on desktop-based virtual reality indicates that learning can similarly be explained through affective and cognitive pathways involving constructs such as presence, usability, and self-efficacy (Makransky and Petersen 2019). These findings suggest that core psychological mechanisms central to CAMIL are not exclusive to fully immersive VR but may also be observable in less immersive configurations. A detailed discussion of CAMIL and its six dimensions is provided in Section 2.3.

1.4. The Present Study

This study introduces GeoMETriA, a metaverse-based geometry learning platform designed to integrate sign language instruction, interactive three-dimensional models, and avatar-based collaboration for DHH learners. Grounded in CAMIL, GeoMETriA emphasizes psychological affordances of presence and interaction that support engagement and learning. The study examines how DHH students experience metaverse-based learning within GeoMETriA and explores usability and accessibility considerations from both student and teacher perspectives.

This study is guided by the following research questions:

1. How do DHH students experience metaverse-based learning within the GeoMETriA environment in terms of engagement, participation, and interaction?
2. How do key CAMIL dimensions (interest, intrinsic motivation, self-efficacy, embodiment, cognitive load, and self-regulation) manifest in DHH students' engagement within a metaverse-based geometry learning context?
3. What usability and accessibility considerations emerge from teachers' and students' interactions with the GeoMETriA platform, and how do these considerations shape inclusive learning experiences for DHH learners?

By addressing these questions, this study contributes to the emerging literature on inclusive educational technology by offering empirically grounded insights into how immersive learning environments can support engagement, accessibility, and participation among DHH learners. The findings also provide practical implications for the design and implementation of accessible metaverse-based learning environments in special education contexts, particularly within diverse and resource-variable educational settings.

2. Literature Review

2.1. The Metaverse in Education and Its Core Affordances

The metaverse gained significant visibility in education research and practice following Facebook's rebranding to Meta in 2021, which intensified public and scholarly interest in immersive digital environments for learning (Kaddoura and Al Husseiny 2023; Ng 2022). In educational research, the concept of the metaverse is distinct from Meta's proprietary platform. Rather than referring to a single product, it is commonly understood as a network of persistent and shared virtual environments that support real-time interaction,

continuity of experience, and digital identity representation through avatars (Kye et al. 2021; Mystakidis 2022; Zhang et al. 2022b).

These characteristics are enabled by several interconnected technological infrastructures, particularly artificial intelligence (AI), extended reality technologies, and distributed computing systems that support immersive multi-user environments at scale (Huynh-The et al. 2023; Hwang and Chien 2022; Park and Kim 2022; Uddin et al. 2024). Within immersive technologies, virtual reality (VR) refers to fully simulated digital environments, whereas augmented reality (AR) overlays digital elements onto the physical world (Milgram and Kishino 1994). Mixed reality (MR) integrates real and virtual elements within a shared environment, while extended reality (XR) is commonly used as an umbrella term that encompasses VR, AR, and MR technologies (Park and Kim 2022).

The educational value of these environments stems from several core affordances. First, immersive presence allows learners to experience a sense of "being there" within three-dimensional spaces, enhancing engagement and emotional connection with learning content (Makransky and Petersen 2021; Slater and Wilbur 1997). Second, avatar-mediated interaction enables identity expression, social presence, and collaborative learning through digital representations (Lee et al. 2023a; Nowak and Waddell 2018; Teng et al. 2023). Third, spatial navigation and object manipulation support embodied cognition, allowing learners to interact with digital content in ways that static materials cannot achieve (Johnson-Glenberg 2018; Petersen et al. 2022). Educational platforms such as Second Life, Decentraland, Sandbox, and Minecraft illustrate these affordances by enabling real-time collaboration, avatar-based communication, and interactive simulations that reshape virtual pedagogy.

Recent years have also seen rapid growth in scholarly research on metaverse-based education, reflecting increasing interest in its pedagogical potential across disciplines. Empirical studies have explored applications in areas such as language learning, science, mathematics, engineering, and the arts, with many reporting positive outcomes including increased motivation, engagement, and collaborative learning (Asiksoy 2023; Tlili et al. 2022; Villalonga-Gomez et al. 2023). As shown in Figure 1, the number of Scopus-indexed publications on metaverse education rose sharply from fewer than twenty per year before 2021 to more than 1400 by 2024. This rapid growth highlights the timeliness of developing innovative metaverse-based learning environments, particularly those designed to support learners with diverse educational needs.

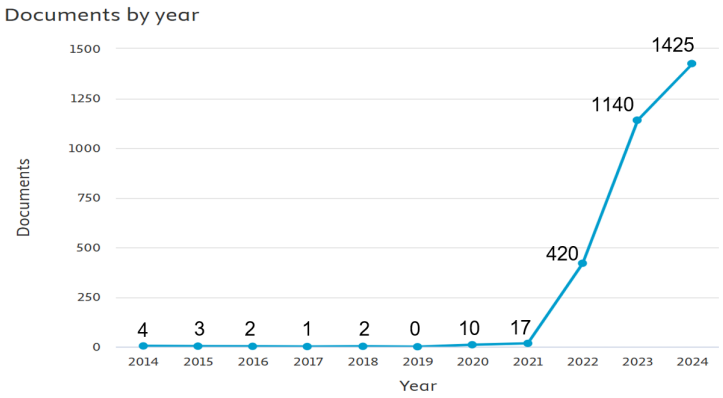


Figure 1. Bibliometric Analysis of Scopus-Indexed Publications on the Metaverse in Education (2014–2024). Search query: (TITLE-ABS-KEY ("metaverse") AND TITLE-ABS-KEY ("learn*" OR "education" OR "train*" OR "teach*")) AND PUBYEAR > 2002 AND PUBYEAR < 2025 AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (PUBYEAR, 2024)). Data was retrieved from Scopus on 7 March 2025.

2.2. Metaverse-Based Learning for DHH Students

Deaf and Hard-of-Hearing (DHH) learners constitute a heterogeneous population, varying in degree of hearing loss, language modality, communication practices, and sociocultural identities. These differences shape access to classroom discourse and necessitate differentiated, culturally responsive instructional approaches (Marschark and Spencer 2010; Silvestri and Hartman 2022). Effective learning environments for DHH students prioritize visual clarity, spatial representation, and accessible communication. These needs align with core affordances of metaverse-based learning: avatar-mediated interaction, visually embodied communication, and interactive spatial representations that support meaning-making beyond auditory channels (Braguez et al. 2023; Zhang et al. 2022b). Features such as sign language explanations, captioning or vibration substitutes for sound, and game-like tasks reduce reliance on auditory input and promote inclusive participation (Alam et al. 2024; Bedard and Zhang 2023; Damasceno et al. 2024).

Empirical research further suggests that metaverse-based learning environments may strengthen social interaction and support learners' confidence and self-efficacy, including among learners with diverse learning needs, while also being associated with reduced feelings of loneliness or social disconnection in some contexts (Lee et al. 2023b; Oh et al. 2023). For DHH learners in particular, visually interactive environments that provide consistent linguistic access and structured opportunities for peer collaboration are especially valuable (Mayer and Trezek 2023).

Within mathematics education, geometry is particularly well suited to metaverse-based learning due to its inherently visual and spatial nature. Research on embodied cognition suggests that mathematical understanding develops not only through visual input but also through action, gesture, and interaction with material or digital representations (Boonstra et al. 2023; Walkington et al. 2024). In geometry learning, learners often construct understanding by coordinating visual and spatial experiences across multiple representations (Arcavi 2003; Duval 2006).

From this perspective, immersive environments are pedagogically meaningful not merely because they provide visual information, but because they allow learners to engage bodily with mathematical objects and relationships, thereby supporting spatial reasoning and embodied interaction (Thom and Hallenbeck 2021). Virtual environments further extend these possibilities by enabling learners to manipulate three-dimensional objects, explore spatial relationships dynamically, and engage in collaborative problem solving (Hwang et al. 2023; Song et al. 2023).

Studies of immersive learning applications have reported improvements in spatial reasoning when instructional designs emphasize hands-on interaction and experiential learning principles (Abylkassymova et al. 2025; Andriyani et al. 2022). However, translating these technological affordances into sustained learning benefits requires a theoretically grounded understanding of how metaverse environments shape learners' cognitive, affective, and social experiences.

2.3. Cognitive Affective Model of Immersive Learning in Metaverse-Based Education

The Cognitive Affective Model of Immersive Learning (CAMIL) provides a research-based theoretical framework for understanding learning in immersive virtual reality through two key psychological affordances, presence and agency. These affordances influence six interrelated dimensions, including interest, intrinsic motivation, self-efficacy, embodiment, cognitive load, and self-regulation, which together explain how learners engage with immersive experiences.

2.3.1. Interest and Intrinsic Motivation

Interest and intrinsic motivation are widely recognized as critical drivers of engagement in immersive learning environments. Research demonstrates that game-based elements, interactive tasks, and multiplayer features can enhance learners' interest and sustain motivation across a range of educational contexts (Heryanto et al. 2024; Shi et al. 2022). Self-Determination Theory highlights the importance of autonomy, competence, and relatedness in fostering intrinsic motivation within technology-enhanced environments (Ryan and Deci 2000). For DHH learners, visually interactive environments and immediate feedback mechanisms may serve a compensatory function by replacing auditory engagement cues with visually salient forms of interaction (Akrami and Shirvani 2025; Yue and Tang 2025). Visual, feedback-driven activities tailored to DHH perceptual characteristics enhance conceptual understanding, while dual-channel visual feedback systems reduce cognitive load (Yue and Tang 2025).

2.3.2. Self-Efficacy in Virtual Learning Contexts

In metaverse-based learning, self-efficacy, defined as a learner's belief in their ability to succeed at specific tasks, plays an important role in shaping learners' engagement and interaction within immersive environments. Studies suggest that immersive platforms enhance self-efficacy by enabling dynamic content interaction, identity expression through avatars, and collaborative peer engagement (Farikah et al. 2023; Pendergast et al. 2022). Virtual learning environments foster a sense of competence and belonging, which encourages active participation and strengthens self-confidence. Evidence from 3D virtual classroom implementations indicates that such active, ownership-oriented engagement can be accompanied by increases in self-efficacy over time (Pendergast et al. 2022). For DHH students who may experience reduced self-efficacy in traditional mathematics classrooms due to communication barriers, metaverse environments offering visual mastery experiences and peer collaboration may help address these challenges.

2.3.3. Embodiment and Presence

Embodiment refers to the sensation of being immersed in a virtual environment and controlling a digital representation, typically an avatar (Guy et al. 2023). Research suggests that embodied cognition enhances learner engagement and comprehension by allowing learners to interact physically with digital content (Makransky and Petersen 2021). Avatar customization and interactive engagement support identity expression and avatar identification, which are associated with heightened social presence and psychological connection (Lee et al. 2023a; Zimmermann et al. 2023).

These affordances benefit DHH learners particularly when environments emphasize clear visual access and shared visual attention, given their greater reliance on visual channels (Marschark et al. 2017). In geometry education, embodied interaction with three-dimensional representations supports conceptual understanding through movement, manipulation, and perspective-taking (Boonstra et al. 2023). However, evidence for generalized visual-spatial superiority among DHH learners remains mixed, and empirical research on embodied geometry learning in this population is limited (Blatto-Vallee et al. 2007; Marschark et al. 2015b).

2.3.4. Cognitive Load in Immersive Environments

While immersive environments enhance engagement, they may increase cognitive load if instructional design is not aligned with learners' processing capacities. Cognitive Load Theory emphasizes that excessive extraneous load from poorly structured instruction hinders learning efficiency (Sweller 1988). CAMIL similarly highlights the need to balance

immersion with structured scaffolding to prevent cognitive overload (Makransky and Petersen 2021).

For DHH learners, immersive environments can impose additional cognitive demands due to the simultaneous processing of visual content, sign language input, text, and interactive elements. Research indicates that overlapping multimodal information strains working memory and increases cognitive fatigue (Luft and Brochu 2023; Rodrigues et al. 2022b). Adaptive pacing, clear visual organization, and structured scaffolding help manage these demands effectively (Kato and Kitamura 2021; Samaradivakara et al. 2024).

2.3.5. Self-Regulation in Immersive Educational Settings

Self-regulated learning refers to learners' ability to plan, monitor, and adapt cognitive and motivational processes to achieve learning goals (Pintrich 2000; Zimmerman and Schunk 2011). In immersive environments, self-regulation is critical because learners must navigate visually complex spaces, manage progress, and sustain engagement with reduced instructional guidance. Insufficient guidance can lead to disorientation and difficulties in self-regulation (Makransky et al. 2019; Mayer et al. 2023).

Immersive technologies support self-regulation when design incorporates feedback, progress cues, and learner-controlled pacing that scaffold planning and monitoring. Signaling-based guidance enhances self-regulated learning and task performance, while poorly structured experiences increase cognitive demands and distract from learning goals (Makransky and Lilleholt 2018). For DHH learners, effective self-regulation is closely tied to instructional design, as learning requires sustained visual attention across multiple information sources. Structured guidance and clear task organization enhance engagement and autonomy, suggesting that self-regulation should be scaffolded through design rather than assumed as innate (Farikah et al. 2023; Petersen et al. 2022).

2.4. Research Gaps and Study Rationale

The preceding review reveals several gaps in the existing literature. First, although metaverse-based learning environments have been shown to enhance engagement and motivation (Asiksoy 2023), most empirical studies focus on hearing learners in general education contexts (Mirzaei et al. 2020). Research on DHH students' metaverse-based learning experiences, particularly in mathematics and geometry, remains limited.

Second, while CAMIL provides a robust framework for examining immersive learning, its application to learners with sensory disabilities is underexplored. Little is known about how CAMIL dimensions manifest among DHH learners whose learning is predominantly visual and shaped by distinct linguistic experiences.

Third, existing metaverse platforms are largely designed for hearing users, with accessibility features often implemented as secondary adaptations rather than as core design principles (Creed et al. 2024; Othman et al. 2024). Empirical research examining purpose-built, accessibility-centered metaverse platforms for DHH learners remains scarce (Tlili et al. 2022).

Finally, few studies integrate both student and teacher perspectives when evaluating immersive learning environments for DHH students, limiting understanding of usability and classroom implementation. In response, this study adopts an exploratory qualitative approach to examine DHH students' experiences with GeoMETriA, a metaverse-based geometry learning platform designed to support visual-spatial learning and sign language integration. Guided by CAMIL, the study aims to generate empirically grounded insights that inform future research and inclusive design practices.

3. Methodology

3.1. Research Design

This study employed a multi-phase qualitative design to explore the usability, accessibility, and learning experiences associated with GeoMETriA, a metaverse-based geometry learning platform developed for DHH learners. The study was conducted within the Malaysian educational context, where recent national initiatives, including the Digital Education Policy (DEP) 2023 (Ministry of Education Malaysia 2023) and the Ministry of Education Strategic Plan (PSKPM) 2024–2030 (Ministry of Education Malaysia 2024), promote equitable access and technology-enabled inclusion for learners with special educational needs.

The study was structured across three sequential phases: (1) pre-workshop semi-structured interviews with teachers, (2) a student-centered metaverse-based geometry learning workshop, and (3) a post-workshop focus group discussion (FGD) with students. These phases were integrated sequentially, with interviews informing design expectations prior to implementation and the FGD capturing experiential feedback following platform use, enabling a complementary examination of instructional design intentions, learners' situated experiences, and post-use reflections. The Cognitive Affective Model of Immersive Learning (CAMIL) served as a sensitizing framework, guiding analytic attention to the affective and cognitive dimensions that emerged through students' interactions with the platform.

3.2. Participants

This study employed purposive sampling to recruit two participant groups: special education teachers and DHH secondary students. Four teachers provided professional insights on instructional content, sign language integration, and cognitive load management, while fifteen DHH students engaged with interactive geometry tasks, avatar-based exploration, and gamified learning modules. Of these students, seven participated in a single FGD, followed by individual follow-up questions to clarify incomplete or ambiguous responses. Variation in participants' characteristics, including age, degree of hearing loss, and use of hearing devices, supported sufficient information power in relation to the focused research aim and the use of semi-structured interviews and an FGD (Malterud et al. 2016; Vasileiou et al. 2018).

3.2.1. Teacher Participants

Four special education teachers (3 females, 1 male) with extensive experience in deaf education were recruited from a government secondary school with a Special Education Integration Program (SEIP). Teachers were selected based on the following criteria: (a) a minimum of 10 years of teaching experience with DHH students, (b) proficiency in Manually Coded Malay (Kod Tangan Bahasa Melayu, KTBM) or simultaneous communication, and (c) current involvement in teaching mathematics or related STEM subjects to DHH learners. Table 1 presents the demographic characteristics of teacher participants.

Table 1. Demographic characteristics of teacher participants.

Participant	Gender	Experience in Deaf Education
T1	Female	25 years
T2	Female	11 years
T3	Female	15 years
T4	Male	16 years

3.2.2. Student Participants

Fifteen DHH secondary students were initially recruited for the metaverse-based learning workshop. Eligibility criteria included: (a) documented hearing loss ranging from moderate (30 to <60 dB) to profound (≥90 dB), (b) use of KTBM or simultaneous communication as the primary mode of communication, (c) no concurrent visual impairments affecting screen-based learning, (d) basic digital literacy enabling independent computer use, and (e) completed informed consent from guardians and written assent from students.

Following the workshop, seven students (S1–S7; 3 females, 4 males) aged 15–17 years were purposively selected to participate in FGD. This group size aligns with recommendations for small-scale groups, which are commonly used to elicit in-depth experiential perspectives from participants with specialized knowledge (Cortini et al. 2019; Krueger and Casey 2014). Extended discussion time was also provided to support visually mediated communication, as focus groups involving DHH participants often require greater time and patience to ensure meaningful interaction (Balch and Mertens 1999). Selection was based on variation in observed engagement levels during the workshop, degree of hearing loss, and willingness to participate in extended discussion. Table 2 presents the demographic, audiological, and communication characteristics of student participants in the FGD phase.

Table 2. Demographic, audiological, and communication characteristics of student participants.

Participant	Gender	Age	Degree of Hearing Loss	Hearing Device(s)	Communication Mode
S1	Female	16	Profound (≥90 dB)	Hearing aids	Sign language
S2	Male	16	Profound (≥90 dB)	None	Sign language
S3	Male	15	Profound (≥90 dB)	None	Sign language
S4	Female	15	Moderate (30 to <60 dB)	Cochlear implant	Sign-supported speech
S5	Male	17	Profound (≥90 dB)	Hearing aids	Sign language
S6	Male	16	Moderate (30 to <60 dB)	Hearing aids	Sign-supported speech
S7	Female	16	Moderate (30 to <60 dB)	None	Sign-supported speech

Note: Hearing levels were classified based on audiological thresholds of the better ear, in accordance with national disability registration guidelines issued by the Ministry of Health Malaysia.

3.3. Ethical Considerations

This study received ethical approval from the relevant research ethics committee and adhered to institutional guidelines for research involving human participants. Parental or guardian informed consent and participants' assent were obtained prior to data collection, with assent treated as an ongoing process throughout participation (Askari et al. 2024; Parekh et al. 2021; Wittich et al. 2023). Participation was voluntary, and participants were informed of their right to withdraw at any stage without penalty or negative consequences (Dahal 2024; Karnieli-Miller et al. 2009; Parekh et al. 2021).

Confidentiality and anonymity were ensured through the use of pseudonymous codes (T1–T4 for teachers; S1–S7 for students), with identifiable information removed during transcription and analysis (Heaton 2022). Data were securely stored and accessed only by the research team for academic purposes (Wang et al. 2026).

Given the involvement of DHH students, particular attention was paid to communication accessibility. Participants were able to communicate using spoken language, sign language, or a combination of both, ensuring equitable participation and comprehension throughout the study (McKee et al. 2013; Wittich et al. 2023).

3.4. Data Collection Procedures

3.4.1. Phase 1: Pre-Workshop Teacher Interviews

The first phase involved semi-structured interviews with four experienced special education teachers specializing in deaf education. The interviews examined instructional clarity and accessibility, with particular attention to the integration of sign language videos and visual explanations. They also explored interactivity and engagement, including the suitability of immersive and gamified geometry tasks for Deaf and Hard-of-Hearing (DHH) learners, as well as cognitive load and usability considerations related to interface design, navigation, and potential barriers for novice users. Insights from this phase informed refinements to instructional flow, sign language presentation, and task sequencing prior to student implementation.

3.4.2. Phase 2: Student Workshop Implementation

The second phase consisted of a four-session metaverse-based workshop involving 15 DHH secondary students aged 15 to 17. GeoMETriA was developed using Mitoworld (https://mitoworld.io, accessed on 10 September 2025), a browser-based metaverse platform that supports customizable three-dimensional environments and real-time multiplayer interaction. The platform incorporated sign language instructional videos, interactive geometry learning activities, and gamified features tailored to the learning needs of DHH students. The workshop activities were aligned with selected topics from the Standards-Based Curriculum and Assessment Document (DSKP), Malaysia's national framework guiding teaching, learning, and assessment in the secondary curriculum, particularly the chapters on Lines and Angles and Basic Polygons. However, only concepts that could be effectively represented through spatial visualization and interactive manipulation within the metaverse environment were implemented. Despite differences in age, students' prior geometry knowledge was broadly comparable, reflecting commonly reported challenges in spatial reasoning and mathematical problem-solving among DHH learners associated with limited access to auditory instruction (Pagliaro and Ansell 2012; Schindler et al. 2022).

The workshop followed a scaffolded progression to reduce initial navigation demands and support gradual task fluency within the metaverse environment. Sessions 1 and 2 focused on platform readiness, including account setup, navigation, and avatar customization. Session 3 emphasized hands-on geometry tasks and provided access to MathsPad (https://www.mathspad.co.uk, accessed on 14 October 2025), an external interactive geometry tool embedded within GeoMETriA to support construction activities using virtual compasses, rulers, and protractors. Session 4 involved a multiplayer metaverse quiz developed using Zep Quiz (https://quiz.zep.us, accessed on 20 October 2025) to assess conceptual understanding and learner engagement. Across all sessions, instructions were delivered through visually accessible modalities, including sign language videos, on-screen prompts, and teacher facilitation. Table 3 summarizes the workshop structure.

Table 3. Workshop structure.

Session	Activity	Description
Session 1	Introduction and Orientation	Students were introduced to the metaverse platform, including account setup, navigation, and basic interaction (Figure 2).
Session 2	Avatar Customization and Virtual Navigation	Students personalized avatars and practiced movement, teleportation, and object interaction (Figure 3).

Table 3. *Cont.*

Session	Activity	Description
Session 3	Hands-on Geometry Tasks	Students completed sign language-guided geometry activities using digital tools (e.g., instructional videos, drawing line segments, measuring angles) and played educational games to reinforce concepts (Figure 4).
Session 4	Interactive Assessment	Students participated in collaborative discussions and completed a multiplayer metaverse quiz to assess conceptual understanding and engagement (Figure 5).



Figure 2. GeoMETriA metaverse learning environment used in the student workshop.

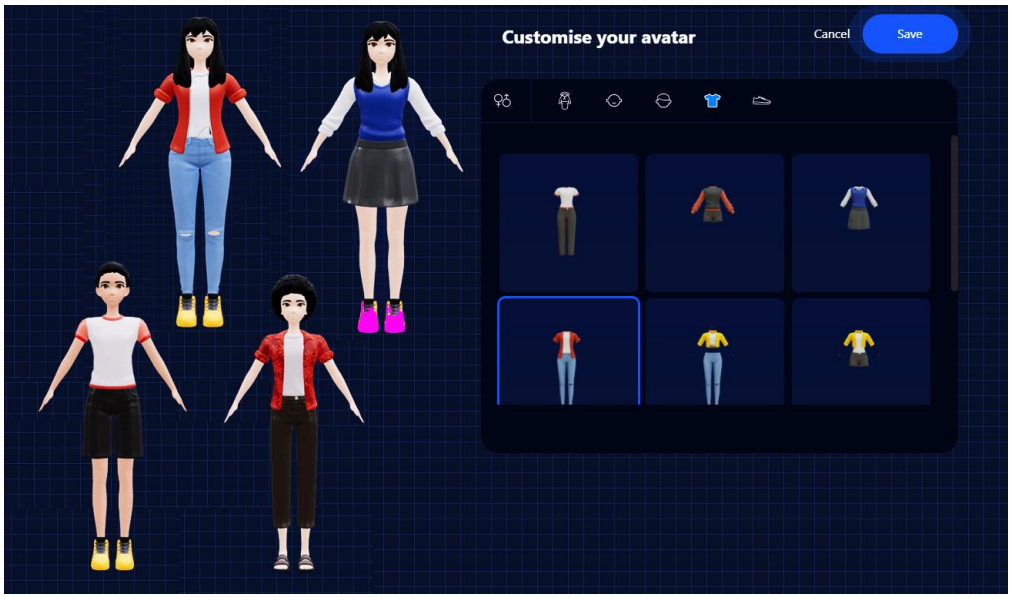


Figure 3. Avatar customization in the metaverse platform.

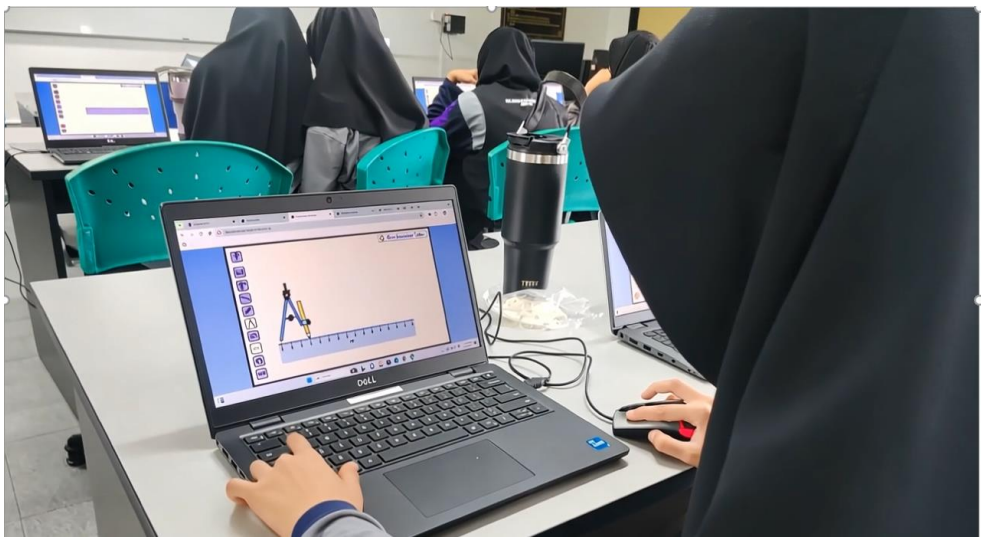


Figure 4. Students engaging in geometry learning activities during the workshop.

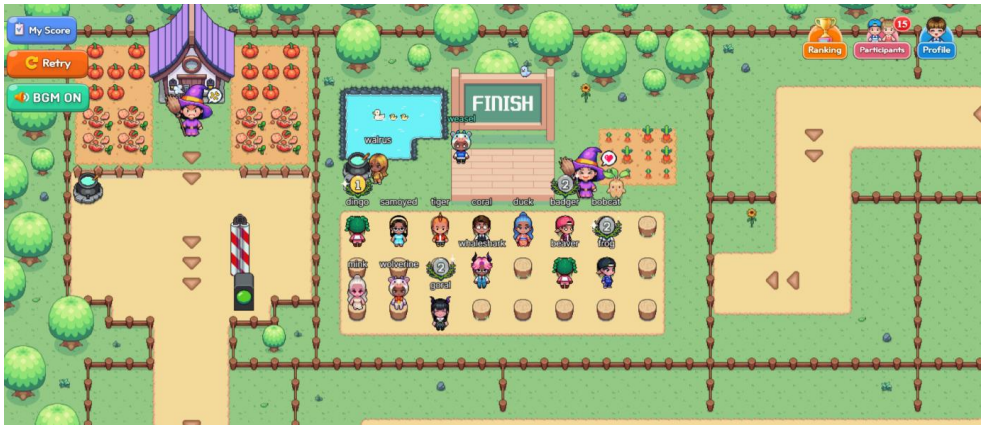


Figure 5. Multiplayer quiz environment used for interactive assessment. The numbered icons above the avatars indicate players' ranking during the multiplayer quiz activity.

3.4.3. Phase 3: Post-Workshop Focus Group Discussion (FGD)

Following the workshop, seven students participated in an FGD to reflect on their learning experiences. The FGD was moderated by the first author, while a special education teacher familiar with the participating students assisted as a facilitator to support communication during the discussion. The session lasted approximately 45 min and was conducted in the school setting using KTBM, spoken Malay, and other multimodal supports to ensure accessible communication. The discussion was video-recorded with participants' consent. Guided by CAMIL dimensions, the discussion explored students' perceptions of task complexity and cognitive load, changes in self-efficacy and motivation associated with avatar customization and gamified activities, and the social and collaborative learning dynamics that shaped engagement and knowledge construction.

3.5. Data Analysis and Trustworthiness

Pre-workshop semi-structured interviews were analyzed descriptively to summarize teachers' expectations, concerns, and design-related insights regarding GeoMETriA's usability and accessibility. Analysis involved close reading of transcripts to preserve participants' language and contextual meaning, consistent with qualitative descriptive approaches (Sandelowski 2000). Post-workshop FGD with seven student participants was analyzed using thematic analysis supported by ATLAS.ti 24. The analysis followed Braun

and Clarke's (2006) six-phase framework, comprising familiarization with the data, initial coding, theme generation, theme review, theme definition, and reporting. Although the interview and FGD protocols were informed by CAMIL, themes were generated inductively from participants' responses and subsequently interpreted using CAMIL as an analytical lens (Fereday and Muir-Cochrane 2006).

To enhance trustworthiness, several strategies were employed. First, the interview and FGD protocols were reviewed by three experts in special education to ensure conceptual clarity, relevance, and alignment with the study objectives, thereby strengthening content adequacy prior to data collection. Second, member checking was conducted with a subset of participants, involving one teacher (T1) and two students (S1, S4). These participants reviewed the researchers' interpretations to confirm that the findings accurately reflected their intended meanings. Participation in this step is reported transparently, consistent with qualitative validation practices aimed at supporting credibility in interpretive research (Birt et al. 2016; Lincoln and Guba 1985).

3.6. Researcher Positionality

All members of the research team are hearing researchers. The first author is a special education teacher and doctoral candidate in deaf education with working proficiency in Manually Coded Malay (KTBM). She served as the primary field researcher, conducting the teacher interviews and moderating the focus group discussion with student participants. The fourth author, a special education teacher with experience working with students with diverse learning needs, including DHH learners, assisted with data collection. The second and third authors contributed to the research design, analytical oversight, and manuscript preparation. The third author, a lecturer in deaf education with strong proficiency in sign language, also reviewed the interpretation of signed responses during transcription to support translation accuracy. The research team's professional experience in deaf education informed the design of accessible data collection procedures. However, the authors acknowledge that, as hearing researchers, their perspectives may differ from those of members of the Deaf community.

3.7. Translation and Transcription Procedures

The FGD was conducted using a combination of KTBM and spoken Malay to accommodate participants' communication preferences. All sessions were video-recorded to capture both signed and spoken contributions. Responses were first transcribed into written Malay by the first author, who is proficient in KTBM. The transcripts and corresponding video segments were reviewed by the third author, a deaf education lecturer with strong sign language proficiency, to verify the interpretation of signed responses.

The transcripts were then translated into English by the fourth author and reviewed for linguistic accuracy by an English-language teacher experienced in teaching DHH students. Care was taken to preserve the intended meaning of participants' signed expressions rather than producing literal word-for-word translations. Quotations reported in this study therefore represent English translations of participants' original responses in KTBM and spoken Malay.

4. Results

This section reports findings from two qualitative data sources: pre-workshop interviews with four special education teachers and post-workshop FGD with seven DHH students who participated following a four-session GeoMETriA workshop. Findings are organized to address the study objectives, focusing on platform usability and accessibility,

as well as learner experiences across CAMIL-related dimensions including interest, intrinsic motivation, self-efficacy, embodiment, cognitive load, and self-regulation.

4.1. Pre-Workshop Insights

Teacher interviews were conducted prior to the student workshop to capture design-informed perspectives on GeoMETriA. During guided walkthroughs, teachers explored the platform and shared anticipatory judgments grounded in their professional experience teaching DHH students.

4.1.1. Expectations and Challenges of GeoMETriA Through the Lens of CAMIL

Across interviews, teachers expressed strong optimism that GeoMETriA could enhance student engagement and motivation through its visually rich, interactive, and game-oriented design. Many anticipated that the platform would capture learners' attention more effectively than conventional resources by presenting geometry in an experiential and exploratory format. T1 described GeoMETriA as "visually engaging" with "strong potential for supporting DHH students," while T3 noted that it could make abstract geometry "more concrete and easier to understand." These expectations align with CAMIL's affective pathway, in which interest and intrinsic motivation support immersive learning.

Despite this positive outlook, teachers anticipated initial challenges for students unfamiliar with virtual environments or with limited ICT literacy. T2 noted that "some parts initially felt overwhelming," while T3 suggested that students "would likely need more structured guidance to use it effectively." T4 emphasized the importance of onboarding support, recommending tutorials or step-by-step guidance to facilitate navigation. These concerns reflect CAMIL's cognitive load dimension, suggesting that unfamiliar interfaces may impose extraneous load unless supported by clear scaffolding.

Teachers also offered practical design recommendations to improve usability. T1 observed that although "the structure of GeoMETriA is good," the interface "feels somewhat cluttered," and suggested simplifying the layout and adding a "one-tap start option." A clearly labeled, numbered learning pathway was also proposed to guide students through videos, tasks, and quizzes in a logical sequence. Collectively, these suggestions highlight the importance of instructional structure in translating motivational potential into sustained engagement.

4.1.2. Enhancing Usability and Accessibility in GeoMETriA

Teachers consistently described sign language instructional videos as a major accessibility strength. T1 emphasized that the videos "make geometry concepts more accessible," and highlighted that replaying videos "until they understand" is valuable because students often forget prior learning. T3 likewise identified sign language integration as the platform's strongest aspect, noting that these videos make geometry "far more accessible for DHH students." These perspectives position sign-supported instruction as a core element of inclusive access.

At the same time, teachers identified refinements that could strengthen comprehension for diverse learners, particularly those with weaker sign language proficiency. T2 noted that although the videos are "generally good," "some students might find the pacing too fast," which could limit understanding without support. T4 similarly indicated that "slowing down the explanations would make them clearer and easier for students to follow," while T3 suggested that offering "a slower playback option" and embedding "one or two simple questions in the middle of the video" could further support comprehension. These suggestions underscore the value of flexible pacing and formative checks for understanding.

In addition to content accessibility, teachers anticipated that hands-on tools could support learning if initial guidance is provided. T2 emphasized the need for early support,

while T3 expected comfort to increase "with regular practice." T1 described the drawing tools as "visually appealing" and well suited for DHH students, and T4 emphasized that hands-on interaction can be motivating and support deeper understanding. Teachers also raised infrastructure concerns, particularly the need for stable internet access to avoid lag during simultaneous use. Overall, they linked accessibility strengths to thoughtful pacing, guided interaction, and technical readiness.

4.1.3. Gamification and Engagement Factors

Teachers viewed gamification as essential for sustaining interest and encouraging active participation. Games were positioned as motivational tools that make learning enjoyable, particularly for younger learners who prefer interactive, hands-on activities. T1 noted that students "would likely enjoy games such as Kangaroo Jumping," adding that although the games "appear simple," they are "appropriate for the students' learning level." T2 highlighted Shooting Angles as engaging and suggested multiple levels to help students track progress, while T3 emphasized that game-based activities are important for "attracting and maintaining" student interest.

At the same time, teachers stressed that gamification should be embedded within a structured learning flow rather than treated as standalone entertainment. Game elements should connect to guided progressions linking videos, tasks, and quizzes. T1 suggested a progress-focused dashboard, T3 recommended a progress tracker, and T2 proposed a token-based reward system tied to task completion. Teachers further identified social interaction as a strong engagement driver requiring guidance. T2 noted that meeting friends through avatars could increase excitement and immersion, while T4 emphasized peer mentoring for productive use. T3 cautioned that teacher and parental monitoring remains important to keep students focused on learning goals.

In summary, pre-workshop insights suggest that GeoMETriA holds strong potential to enhance motivation and engagement through visual interactivity, sign-supported instruction, and gamified learning. Teachers highlighted critical design and implementation conditions, including onboarding support, simplified navigation, adjustable pacing, and progress monitoring, to ensure these affordances translate into meaningful learning experiences.

4.2. Post-Workshop Insight: Focus Group Discussion

This section presents findings from post-workshop FGD conducted with seven DHH students who reflected on their experiences with GeoMETriA. The discussion was conducted using sign language and other multimodal supports and lasted approximately 45 min. Data were analyzed in ATLAS.ti 2024. The analysis produced 69 quotations that were coded into 15 descriptive codes (Figure 6), capturing salient aspects of engagement, learning support, and usability challenges reported by students.

Avatar Customization and Identity emerged as the most frequently coded category (n = 10), indicating that personalization and identity expression within the metaverse played a central role in shaping students' engagement. This was closely followed by Enjoyment Through Gamification (n = 9), reflecting the motivational impact of game-based learning activities. Other highly represented codes included Interactivity and Environmental Realism (n = 6), Peer Learning and Collaboration (n = 6), and Scaffolding Needs (n = 6), reinforcing the importance of immersive features, social interaction, and instructional support in DHH students' metaverse learning experiences.

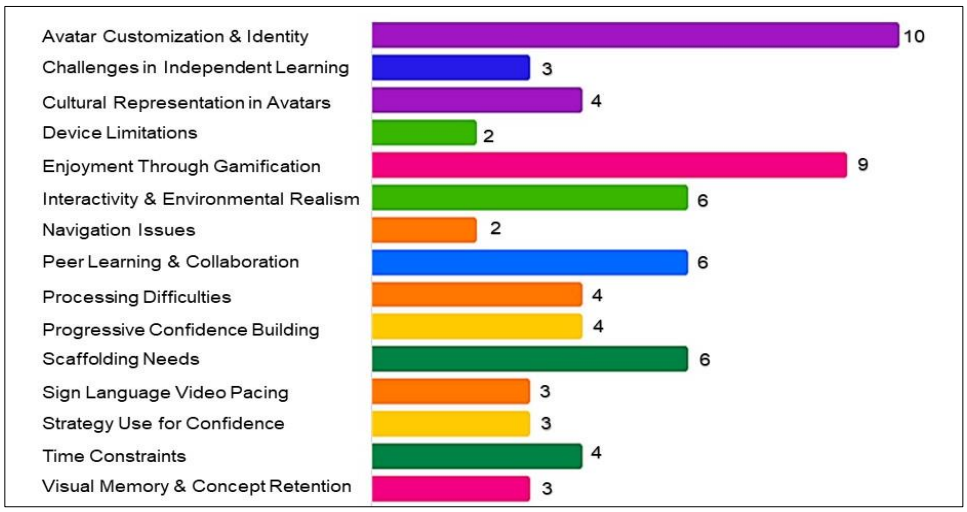


Figure 6. Frequency of codes emerging from the FGD. Numbers at the end of each bar indicate the frequency with which each code appeared in the focus group discussion data.

At the interpretive level, the 15 codes were synthesized into six overarching themes with fifteen sub-themes: Interest and Engagement, Embodiment and Virtual Presence, Self-Efficacy and Confidence Development, Social Learning and Self-Regulation, Cognitive Load and Learning, and Usability and Accessibility (Figure 7). Table 4 summarizes the alignment between these themes, the study objectives, and CAMIL-related constructs, including interest, intrinsic motivation, self-efficacy, embodiment, cognitive load, and self-regulation.

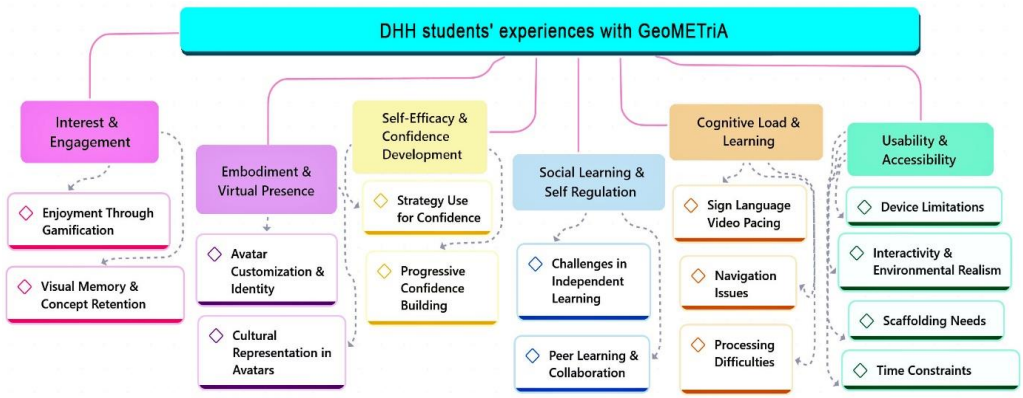


Figure 7. Thematic map of DHH students' experiences with GeoMETriA. Dotted arrows indicate relationships between themes and sub-themes.

Table 4. Themes, CAMIL Constructs and Student Learning Experiences.

Theme	CAMIL Dimension	Description (Student Experience)
Interest and Engagement	Interest, Intrinsic Motivation	Gamified tasks supported enjoyment and sustained participation; multiplayer/competition increased involvement; visual exposure supported concept recall.
Embodiment and Virtual Presence	Embodiment	Avatar customization supported identity and presence; movement enhanced immersion; limited cultural options reduced relevance for some students.

Table 4. *Cont.*

Theme	CAMIL Dimension	Description (Student Experience)
Self-Efficacy and Confidence Development	Self-Efficacy	Confidence increased from initial uncertainty through practice and teacher scaffolding; worked examples supported task completion.
Social Learning and Self-Regulation	Self-Regulation	Students preferred learning with peers; collaboration supported motivation and problem-solving; learning alone reduced engagement.
Cognitive Load and Learning	Cognitive Load	Limited scaffolding, fast sign-video pacing, and navigation issues increased cognitive demands; students requested slower pacing and clearer guidance.
Usability and Accessibility	Non-CAMIL (platform/context)	Device and time constraints disrupted learning continuity; students suggested stronger guidance, improved interactivity, and added environmental realism.

4.2.1. Gamification and Social Engagement: Enhancing Interest and Motivation

Students consistently described the learning experience as enjoyable, particularly when activities involved games, competition, and peer participation. In response to the opening prompt, students collectively signaled that the experience felt "fun," with several explaining that the platform allowed them to "play and learn at the same time." Competition heightened engagement further, as students described excitement in racing to select the correct shape during gameplay.

Beyond enjoyment, students linked gameplay to visual memory and concept retention, noting that repeated exposure to shapes helped them remember geometry vocabulary more effectively. Students attributed improved understanding to multimodal presentation, including captions alongside sign language. These findings suggest that gamified and socially interactive features promoted interest and motivation while strengthening geometry vocabulary and conceptual recall. Table 5 summarizes the key sub-themes and supporting excerpts.

Table 5. Interest and engagement sub-themes.

Sub-Theme	Exemplar Quotes	Interpretation
Enjoyment Through Gamification	"Fun! I can play and learn at the same time." (S1) "I like to compete with friends. It's exciting to see who can jump to the correct shape first." (S5)	Game-based and competitive activities enhanced enjoyment and sustained engagement, increasing students' willingness to participate in geometry learning tasks.
Visual Memory and Concept Retention	"After playing, I remember the names of the shapes better. The captions along with sign language, it helps me understand better." (S3) "I remember shapes like triangle, square because I see them in the game." (S4)	Repeated visual exposure and multimodal supports strengthened geometry terms recall and conceptual understanding.

4.2.2. Embodiment and Virtual Presence: Identity and Immersion

Embodiment was most evident in students' emphasis on avatars. Students described avatar selection as enjoyable and personally meaningful, and they associated avatar movement (walking, running, jumping) with a stronger sense of "being inside" the virtual space. However, students also raised concerns about limited customization options, especially regarding cultural representation. Some students reported wanting more clothing options, including culturally relevant items such as a tudung, and suggested that photo-based avatar creation would improve personal relevance and identification with the avatar. These responses indicate that while avatar embodiment supported presence and identity expression, more inclusive customization options may strengthen belonging and comfort for diverse learners (Table 6).

Table 6. Embodiment and Virtual Presence Sub-themes.

Sub-Theme	Exemplar Quotes	Interpretation
Avatar Customization and Identity	"It was fun to choose my own avatar." (S1) "I love running and jumping with my avatar. It feels like I'm really inside the game!" (S7)	Avatar customization supported identity expression and presence, while movement capabilities deepened immersion.
Cultural Representation in Avatars	"I looked for a tudung (headscarf), but I couldn't find one. If there's a choice, I want to wear it for my avatar." (S7) "If we could use our own photo to create an avatar that looks more like us, that would be amazing!" (S6)	Limited cultural options reduced personal relevance. Inclusive avatar representations may strengthen belonging.

4.2.3. Self-Efficacy and Confidence Development: From Uncertainty to Independence

Students described a progression from initial uncertainty to increased confidence over time. Early difficulties with task procedures gave way to greater independence through practice and teacher support. One student noted that they initially struggled with how to write answers, but became accustomed over time. Others highlighted a shift from frequently asking the teacher to being able to complete tasks independently after repeated practice.

Students also described strategy use as supporting their confidence, particularly when reading worked examples before attempting questions. However, confidence was task-dependent: one student reported feeling confident during games but becoming unsure when questions were more difficult. Overall, these patterns suggest that self-efficacy developed through repeated exposure, scaffolding, and accessible supports, aligning with CAMIL's emphasis on confidence as a driver of engagement (Table 7).

Table 7. Self-Efficacy and Confidence Development Sub-themes.

Sub-Theme	Exemplar Quotes	Interpretation
Progressive Confidence Building	"At first, I didn't understand how to write the answers, but after some time, I got used to it." (S1) "After teacher explains, I can do it better by myself." (S3)	Repeated practice and teacher scaffolding facilitated a transition from uncertainty to independence, indicating self-efficacy development.

Table 7. *Cont.*

Sub-Theme	Exemplar Quotes	Interpretation
Strategy Use for Confidence	"I read the examples first, so I feel more confident to answer the questions." (S4) "I feel confident in the games, but the hard questions make me unsure." (S2)	Students using available scaffolds reported greater confidence, though some distinguished between confidence in games versus formal questions.

4.2.4. Social Learning and Self-Regulation: Peer Collaboration and Independent Learning Challenges

Social interaction emerged as a strong motivational driver. Students consistently reported that learning with peers was more enjoyable and effective, describing peer support as a practical resource for checking answers and seeking help. In contrast, learning alone was characterized as boring and less motivating, suggesting that social presence supports persistence and engagement. Collaboration functioned as a self-regulatory support, helping students sustain attention and effort during learning tasks (Table 8).

Table 8. Social Learning and Self-Regulation Sub-themes.

Sub-Theme	Exemplar Quotes	Interpretation
Peer Learning and Collaboration	"I learn better with friends. It makes the learning more enjoyable." (S2) "I can chat and help each other. When I don't understand, I ask my friend to help." (S4)	Students expressed strong preference for collaborative learning, with peer interaction supporting motivation and mutual problem-solving.
Challenges in Independent Learning	"If I do it alone, it feels boring. Studying with friends makes it more fun." (S7) "Learning alone is boring. Better when we have friends to do it together." (S3)	Reduced engagement during independent learning indicates need for structured support during solo tasks.

4.2.5. Cognitive Load and Learning: Processing Challenges, Pacing, and Navigation

Students identified several sources of difficulty that increased cognitive demands. Some reported that questions without guidance were hard to understand, and others described uncertainty in how to solve problems. Attention regulation challenges also emerged, with one student noting they sometimes became distracted and needed reminders to refocus.

Instructional pacing was a key issue in sign language videos. Students valued the videos but reported needing to replay them repeatedly to understand, and they explicitly suggested slower pacing. Navigation issues further contributed to extraneous load, including misclicks when videos were placed too closely. These findings indicate that pacing controls, clearer guidance, and improved layout may reduce extraneous cognitive load and strengthen learning continuity (Table 9).

Table 9. Cognitive Load and Learning Sub-themes.

Sub-Theme	Exemplar Quotes	Interpretation
Processing Difficulties	"No guided questions are hard to understand." (S3) "Sometimes I get distracted and need a reminder to focus." (S6)	Limited scaffolding and unclear questions increased cognitive demands. Some students experienced attention regulation challenges.
Sign Language Video Pacing	"Sign language video is good, but sometimes I had to replay the video many times to understand." (S4) "Make the sign language videos slower." (S3)	Video pacing affected comprehension, requiring replay functionality and slower presentation for effective processing.
Navigation Issues	"Different videos too close, I misclick sometimes." (S6)	Interface layout created extraneous cognitive load through unintended navigation errors.

4.2.6. Usability and Accessibility: Practical Constraints and Design Suggestions

Students highlighted device-related barriers that disrupted access and learning continuity, including difficulty learning on small phone screens and interruptions from laptop battery issues. Students also requested more time to explore activities, suggesting that limited session duration constrained exploration and consolidation.

Additionally, students requested scaffolding for difficult questions and explicit tutorials for angle symbols, indicating that instructional supports remain essential even in engaging immersive settings. Students proposed enhancements to environmental realism and interactivity, such as adding natural or classroom elements and enabling object manipulation (e.g., rotating shapes, changing colors). These suggestions provide concrete directions for iterative refinement (Table 10).

Table 10. Usability and Accessibility Categories.

Sub-Theme	Exemplar Quotes	Interpretation
Device Limitations	"At home, I don't have a laptop. Using a phone is hard because the screen is too small." (S6) "I had to change my laptop twice due to battery issues." (S5)	Device constraints disrupted access and continuity. Platform design should accommodate varied devices.
Time Constraints	"I want more time to explore each activity before moving on." (S1) "One hour feels too short, more time for games would be better." (S2)	Limited session time reduced exploration and consolidation opportunities.
Scaffolding Needs	"Give examples to the difficult questions." (S4) "We need a tutorial on the symbol of angles." (S7)	Students requested worked examples and explicit instruction for mathematical symbols.
Interactivity and Environmental Realism	"It would be fun if avatars could talk in sign language." (S6) "If I can move objects, like rotate a shape or changing colors, feel more like a real place." (S7)	Students desired enhanced interaction capabilities and environmental features to increase realism.

Overall, the FGD findings indicate that DHH students experienced GeoMETriA as highly engaging, with enjoyment driven by gamification, avatar-based embodiment,

and peer presence. However, learning quality depended on manageable cognitive demands, clearer scaffolding, adjustable sign-language pacing, and accessible platform conditions. These results provide an integrated, CAMIL-aligned account of how affective, embodied, social, and cognitive factors intersect in students' metaverse-based geometry learning experiences.

5. Discussion

This study provides empirical insight into how a metaverse-based geometry environment, interpreted through the Cognitive Affective Model of Immersive Learning (CAMIL), can support DHH students' learning by engaging cognitive, affective, and social dimensions (Makransky and Petersen 2021). Rather than positioning GeoMETriA as a standalone technological novelty, the findings indicate that its educational value depends on how immersive affordances are aligned with DHH learners' visual-spatial strengths, sign-supported access needs, and preference for socially mediated learning (Fernandes et al. 2024; Thom and Hallenbeck 2021).

5.1. RQ1: How DHH Students Experienced Learning in GeoMETriA

Students described GeoMETriA as engaging when learning activities were structured as interactive, game-like experiences with peer presence. Enjoyment and sustained participation were consistently linked to gamified tasks, competition, and collaborative play, suggesting that motivational value was derived not from interactivity alone but from social participation within the immersive space. This finding aligns with Lee et al.'s (2023a) research demonstrating that social engagement mediates the relationship between avatar identification and enjoyment. Their study of 301 metaverse users found that avatar identification influenced enjoyment only when social engagement was present, a pattern extending meaningfully to DHH learners who benefit from visually mediated peer collaboration.

Beyond social dynamics, gamification functioned not merely as an entertainment feature but as a mechanism for sustaining attention and reinforcing concept retention. Students reported that repeated visual exposure to geometric shapes during gameplay supported vocabulary recall and recognition, consistent with multimedia learning research emphasizing that redundant visual presentation strengthens memory encoding (Mayer 2005). These findings extend prior research on game-based immersive designs and collaborative social features as drivers of engagement, demonstrating that these affordances operate similarly for DHH learners when sign-language-accessible supports are integrated (Heryanto et al. 2024; Lampropoulos and Kinshuk 2024). These observations are also consistent with Vygotskian perspectives on game-based learning for deaf students, which emphasize collaborative meaning-making and co-construction of knowledge through interactive play (Starosky and Pereira 2013).

However, student experience was shaped by design and access conditions that either supported or constrained participation. When navigation was unclear, sign language videos paced too quickly, or students relied on devices with small screens or unstable connectivity, learning shifted from engaging to effortful. These barriers highlight that immersion supports participation only when usability and accessibility are treated as foundational design requirements rather than supplementary adaptations.

5.2. RQ2: How CAMIL Dimensions Manifested in DHH Students' Engagement

The FGD revealed that CAMIL-related dimensions manifested concretely in students' learning experiences, with affective, embodied, and cognitive factors jointly shaping engagement.

5.2.1. Interest and Intrinsic Motivation

Students' interest was strongly associated with game-based tasks and peer competition, with participants emphasizing that the ability to "play and learn at the same time" sustained their willingness to engage with geometry content. The fact that students frequently referred to the activity as a "game" rather than a lesson may also reflect how game-based environments reduce perceived academic pressure while sustaining engagement with learning tasks (Lampropoulos and Kinshuk 2024). This finding resonates with research demonstrating that gamification enhances intrinsic motivation through immediate feedback, visible progress, and social comparison opportunities (Li et al. 2024; Luarn et al. 2023).

The light competitive elements observed during gameplay also appeared to contribute to students' motivation. Friendly competition among peers created a socially engaging environment in which students compared progress, encouraged one another, and shared enjoyment during the activities. For DHH learners, such social interaction may play an important affective role because learning often occurs within visually shared spaces where attention, communication, and participation are collectively negotiated. The combination of playful competition and collaborative exploration therefore supported engagement not only through cognitive challenge but also through positive social and emotional experiences within the virtual environment (Ryan and Deci 2000).

Notably, relatedness emerged as particularly salient, with participants describing "learning with friends" as essential for enjoyment, while independent learning was often characterized as "boring." This pattern extends metaverse research demonstrating that shared virtual spaces strengthen social presence and learner connectedness (Nguyen and Pham 2024; Song et al. 2023). For DHH learners who may experience communication barriers in traditional settings, peer interaction carries heightened motivational significance. The centrality of peer interaction aligns with Farikah et al. (2023), who found that engagement in team-based online learning is closely associated with learners' sense of belonging and comfort within peer groups.

For DHH learners, learning is often closely tied to shared visual interaction and peer communication (Marschark and Spencer 2010). In the present study, the peer group appeared to function not only as a source of social support but also as a context in which visual attention sharing and collaborative meaning-making could occur. When this collective context was removed, students described learning as less enjoyable and less motivating, suggesting that independent learning may reduce not only social engagement but also the communicative conditions that support participation.

5.2.2. Embodiment and Presence

Avatar customization and movement played a central role in shaping students' sense of presence within the virtual learning environment. Students described selecting their avatars as both enjoyable and personally meaningful, and they associated avatar movement, including walking, running, and jumping, with a stronger feeling of "being inside" the space. These experiences support the CAMIL framework's positioning of embodiment as a psychological affordance that facilitates engagement in immersive learning contexts (Makransky and Petersen 2021). The importance of avatar personalization observed in this study resonates with broader research on identity expression in virtual environments. Zimmermann et al. (2023) demonstrated that self-representation through avatars enables learners to construct meaningful connections with digital spaces, while Lee et al. (2023a) found that perceived customization freedom significantly moderates the relationship between avatar identification and enjoyment. González Vallejo (2024) similarly argues that avatar-mediated embodiment supports multimodal engagement. These findings extend to DHH learners, whose engagement depends heavily on visual and spatial interaction.

Students' strong emphasis on avatar customization, the most frequently coded category in the FGD data, warrants interpretation. Rather than reflecting a distraction from mathematical objectives, this pattern suggests that identity representation may function as an entry point for engagement in immersive learning environments. For DHH learners, who often encounter limited representation in digital and educational contexts, the ability to visually construct and personalize an avatar can strengthen feelings of recognition, belonging, and social presence within the virtual space. Avatar customization may therefore help establish a sense of personal relevance that encourages learners to engage more actively with subsequent academic activities (Lee et al. 2023a; Nowak and Waddell 2018).

This interpretation is further supported by students' requests for culturally responsive avatar options, particularly the tudung (headscarf), and their suggestion that photo-based avatar creation would enhance personal relevance. In the Malaysian context, where many female students wear the tudung as part of everyday cultural and religious practice, the ability to represent this feature in avatars contributed to a stronger sense of authenticity within the virtual environment. For DHH learners navigating both deaf identity and cultural belonging, avatar representation functions as a site of identity negotiation rather than merely an immersion tool. Research on disability and virtual identity indicates that users with disabilities prefer avatar representations that reflect their lived identities (Zhang et al. 2022a), suggesting that limited representational options may constrain the very sense of presence that CAMIL identifies as foundational to immersive learning.

5.2.3. Self-Efficacy

Students described a clear progression from initial uncertainty to greater independence. Early reliance on teacher assistance gave way to autonomous task completion as students became familiar with the environment. Several students identified worked examples as particularly helpful, noting that reviewing examples before attempting questions enhanced their sense of preparedness. This developmental pattern aligns with Bandura's (1977) theorization of self-efficacy as shaped by mastery experiences and guided support and is consistent with research demonstrating that structured scaffolding supports learners' transition from dependence to competence (Pendergast et al. 2022).

Notably, self-efficacy appeared task-dependent. Students reported confidence during gamified activities but expressed uncertainty when encountering more difficult questions without guidance. This pattern suggests that immersive environments may support self-efficacy differentially depending on task structure and available scaffolds. The finding extends Lowell and Tagare's (2023) work on authentic learning by highlighting the conditional nature of confidence development for DHH learners navigating unfamiliar digital platforms.

5.2.4. Cognitive Load and Self-Regulation

In participants' accounts, cognitive load and self-regulation appeared closely interrelated, as students simultaneously managed the processing demands of sign language pacing and spatial navigation while monitoring understanding of geometric concepts within the virtual environment. Students reported confusion when questions lacked guidance, navigation errors from dense interface layouts, and the need to repeatedly replay sign language videos. These experiences reflect extraneous cognitive load competing with conceptual processing (Sweller 1988). Notably, the challenges appeared related less to geometry's inherent complexity and more to interface design and pacing decisions, placing unnecessary demands on visual attention and working memory. This interpretation aligns with Cognitive Load Theory's emphasis on reducing extraneous load through streamlined instructional design (Mayer 2005; Sweller 1988), complementing emerging work on cogni-

tive demands faced by DHH learners in digital settings (Luft and Brochu 2023; Rodrigues et al. 2022a; Samaradivakara et al. 2024).

Self-regulation challenges also emerged, with at least one student describing attention difficulties and needing reminders to maintain focus. This suggests immersive environments may introduce distractions despite their motivational affordances, a concern documented in VR learning research (Hsu et al. 2025; Makransky et al. 2019; Mayer et al. 2023). In response, metaverse platforms designed for DHH learners may benefit from embedded metacognitive supports, such as progress indicators, timely prompts, and structured checkpoints, that help learners monitor progress and reorient attention during tasks (Wang et al. 2024). Framing these supports as design elements is consistent with the view that self-regulation is not a fixed individual trait but a set of learnable, context-sensitive processes that can be strengthened through scaffolding and feedback (Boekaerts and Niemivirta 2000; Zimmerman 2002).

5.3. RQ3: Usability and Accessibility Considerations for Inclusive Metaverse Learning

Both teacher-facing concerns and student experiences converge on a critical insight: accessibility in metaverse-based learning must be conceptualized as an ecological condition encompassing infrastructure, interface design, and implementation context, not solely as a property of instructional content. This reinforces arguments in inclusive technology scholarship that technological sophistication does not guarantee inclusion when platforms assume normative interaction modes or overlook practical constraints faced by learners with diverse sensory profiles (Creed et al. 2024; Dudley et al. 2023).

5.3.1. Sign Language Integration as Foundational Accessibility

Teachers and students consistently identified sign language instructional videos as the platform's most essential accessibility feature, underscoring the central role of visual linguistic access in supporting DHH learners' engagement. This finding is consistent with research demonstrating that multimedia materials incorporating sign language enhance learning outcomes for DHH students, particularly when visual language aligns with instructional task demands (Almalhy 2022; Krasavina et al. 2022; Saad Elfar et al. 2024).

At the same time, students' requests for adjustable pacing and teachers' recommendations for embedded comprehension checks suggest that sign language effectiveness depends not only on presence but on delivery. Linguistic accessibility alone does not translate into effective learning support unless learners have sufficient control over timing, sequencing, and cognitive demands. This aligns with Cheng et al. (2024), who emphasize that motion and visual design in sign-supported materials must allow DHH learners to regulate information flow to manage cognitive load during sign language processing. These insights position sign language integration as foundational but not self-sufficient. Effective implementation requires attention to pacing, learner control, and instructional scaffolding to ensure visual linguistic access meaningfully supports comprehension.

5.3.2. Infrastructural Accessibility and Interface Usability

Device limitations and connectivity instability disrupted learning continuity for several students. These accounts reflect how barriers can be produced by design, where learners' participation becomes constrained by the interaction and interface demands of immersive systems. Dudley et al. (2023) argue that disability in VR/AR can emerge when users' experiences are limited by barriers imposed by the design of the virtual environment or its interfaces.

Navigation emerged as a parallel concern. Teachers anticipated that unfamiliar virtual environments would feel "overwhelming," while students confirmed these predictions by describing misclicks and sequencing uncertainty. This convergence suggests that experi-

enced special education teachers possess valuable design knowledge informing accessible platform development, consistent with participatory design approaches in inclusive technology scholarship (Hadi Mogavi et al. 2023; Parker et al. 2024). Teachers' recommendations, including numbered pathways and simplified layouts, offer actionable guidance aligned with CAMIL's emphasis on structuring learner agency while mitigating extraneous cognitive load (Makransky and Petersen 2021).

5.3.3. Toward Ecological Accessibility

While existing discussions of accessibility in immersive environments have largely focused on spatial navigation and communication-related access (Creed et al. 2024; Dudley et al. 2023), DHH learners may require extended processing time when learning environments demand attention to multiple simultaneous visual sources, creating split visual attention demands (Luft and Brochu 2023). This temporal dimension of accessibility remains comparatively underexplored.

International advocacy organizations have long emphasized that Deaf individuals require education access in their national sign languages and that many digital environments fail to provide this adequately (World Federation of the Deaf 2020). The present findings illuminate a specific reason for this gap: accessibility failures often arise not at isolated points but at the intersections of infrastructure, interface design, and implementation context. These findings point toward the importance of ecological accessibility, an approach that recognizes how device configurations, pacing flexibility, navigation supports, and implementation conditions interact to shape learners' experiences (Luft and Brochu 2023; Othman et al. 2024; Damasceno et al. 2024; Zallio and Clarkson 2022).

For metaverse-based deaf education, ecological accessibility therefore involves designing platforms that function across diverse devices, provide adjustable pacing and simplified navigation, and ensure that implementation contexts allow sufficient time and technical support for learners. This perspective shifts the focus from isolated accessibility features to the learning environment as a whole, emphasizing the need to coordinate technical, instructional, and institutional conditions to support meaningful participation for DHH students.

6. Implications

6.1. Theoretical Implications

This study extends empirical understanding of how DHH students experience metaverse-based geometry learning when interpreted through CAMIL. Previous CAMIL applications have predominantly examined hearing learners in immersive digital environments, including VR, XR, and metaverse-based settings (Bartels and Hahne 2023; Petersen et al. 2022; Zhi and Wu 2023). By situating CAMIL within a desktop-based metaverse environment designed specifically for DHH students, this study extends the model's applicability to inclusive educational technology contexts that have received limited empirical attention.

Two theoretical extensions emerge from the findings. First, embodiment appeared to function not only as a mechanism of immersion but also as a socio-cultural resource through which learners express identity and develop a sense of belonging within virtual learning environments (Chee 2007; O'Connor 2016). Students' emphasis on avatar customization, requests for culturally representative features such as the inclusion of a tudung, and interest in expressive actions such as waving and facial expressions suggest that presence for DHH learners is closely connected to recognition, identity representation, and social belonging within the virtual space. These observations indicate that embodiment in

immersive learning environments may support not only perceptual immersion but also socio-cultural participation.

Second, cognitive load in this context was shaped by distinct visual communication demands (Marschark et al. 2005; Rodrigues et al. 2022a). Students reported difficulties related to sign language video pacing, misclicks caused by interface spacing, and challenges in regulating attention across multiple visual elements. These experiences indicate that information processing often requires learners to shift attention across several concurrent visual sources, rendering processing functionally sequential and increasing extraneous cognitive load. When visual elements are spatially or temporally misaligned, such split visual attention further intensifies working memory demands (Schmidt-Weigand et al. 2010).

These patterns highlight the need for CAMIL-informed interpretations that account for how accessibility features, interface layout, and visual attention demands jointly shape cognitive processing for learners who rely primarily on visual modalities (Makransky and Petersen 2021). In immersive environments designed for DHH learners, the relationship between multimodal input and cognitive load becomes particularly salient because multiple visual channels, including sign language, textual captions, and spatial interaction, often operate simultaneously.

Skyer's (2023) concepts of multiplicative multimodal transduction and divided visual attention offer a useful framework for refining this interpretation. Multiplicative multimodal transduction occurs when multiple communicative modes reinforce one another to deepen understanding, while divided visual attention arises when these modes compete for limited processing capacity, increasing cognitive load rather than supporting comprehension. In the present study, both processes were observed: sign language videos combined with captions and geometry visuals supported concept retention, while densely arranged interface elements and rapid visual input created competing attentional demands.

These findings suggest that multimodality in immersive environments should not be assumed to be inherently beneficial but evaluated in terms of whether multiple modes complement or compete with one another. Integrating CAMIL with insights from multimodal theory in deaf education thus provides a more nuanced account of how immersive environments can support engagement while managing cognitive load in visually mediated learning contexts (Makransky and Petersen 2021; Skyer 2023).

6.2. Practical Implications

Practically, the findings offer design and implementation guidance for metaverse-based instruction for DHH students. Sign language integration was consistently valued, but its effectiveness depended on pacing and control. Students described replaying videos repeatedly and requested slower delivery, suggesting that platforms should include adjustable playback speed, segmented clips, and brief comprehension checks to support varied sign proficiency levels.

Students also suggested that avatars could communicate using sign language, highlighting an important accessibility consideration for immersive learning environments designed for DHH users. Recent advances in sign language animation and avatar-based signing systems suggest that such features are becoming increasingly feasible (Alam et al. 2024). Sign-capable avatars could support more natural forms of communication within virtual spaces, enhancing linguistic accessibility and strengthening social presence for deaf learners in metaverse environments.

Navigation and onboarding also require intentional support. Students' early confusion and interface-related errors highlight the need for step-by-step tutorials, clearly labeled learning pathways, and improved spacing of interactive elements. Engagement

was strongly supported by gamification and peer presence (Lee et al. 2023a), yet students reported reduced enjoyment when learning alone. Design should therefore balance collaborative affordances with support for independent learning, such as progress indicators, prompts, and immediate feedback.

Implementation planning must also account for infrastructural realities. Device constraints, small screens, and unstable access conditions disrupted learning continuity and reduced equitable participation (Dudley et al. 2023). These findings reinforce the argument that ecological accessibility requires attention to the full range of technical and contextual conditions shaping learner experience (Damasceno et al. 2024; Zallio and Clarkson 2022).

7. Limitations and Directions for Future Research

This exploratory study was context-specific and involved a small sample, which limits the breadth and transferability of the findings. The absence of direct learning outcome measures means that the results should be interpreted as empirically grounded design insights rather than evidence of generalized learning effects. In addition, the study focused on a single desktop-based metaverse platform (GeoMETriA) within a Malaysian educational context, and results may not transfer directly to other immersive environments with different interface designs, accessibility configurations, or cultural settings.

Future research should examine longer-term classroom implementation with larger and more diverse DHH samples. Comparative designs that contrast collaborative and independent learning pathways could clarify the role of peer presence in sustaining engagement. Integrating pre- and post-assessments with experiential data would enable evaluation of how CAMIL-related mechanisms support geometry understanding over time. Further studies should also investigate how variations in accessibility design, including sign language delivery formats, navigation structures, and device conditions, shape both learning processes and outcomes in inclusive metaverse environments.

8. Conclusions

This study explored DHH students' experiences with GeoMETriA, a metaverse-based geometry learning platform that integrates sign language instruction, three-dimensional visualization, and avatar-mediated interaction. Using a multi-phase qualitative design guided by the CAMIL, data were generated through pre-workshop teacher interviews and a post-workshop student FGD.

Findings indicate that DHH students' engagement in metaverse-based geometry learning is shaped by the interaction between immersive affordances and accessibility conditions. Gamification and peer collaboration supported sustained engagement, while avatar embodiment functioned not only as a mechanism of immersion but also as a sociocultural resource for identity expression. Self-efficacy developed progressively through scaffolded practice. At the same time, challenges related to cognitive load, navigation complexity, and sign language pacing underscored that immersive potential is realized only when accessibility is embedded as a foundational design principle.

This study extends CAMIL in two ways for DHH learning contexts: by conceptualizing embodiment as a process of identity negotiation, and by highlighting how cognitive load is shaped by split visual attention demands inherent in sign-supported learning. From a practical perspective, the findings emphasize the importance of ecological accessibility, whereby device configurations, pacing controls, navigation supports, and implementation conditions are addressed holistically rather than as isolated features. Metaverse-based platforms hold promise for DHH geometry learning when accessibility is treated as a core design commitment rather than a supplementary adaptation.

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