

RESEARCH PAPER

From Design to Evaluation: Inclusive Animated Avatars for Deaf–Hearing Collaboration in the DALverse Educational Metaverse

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Abstract. *Context:* Educational metaverses are emerging as a promising avenue to make Distance Education (DE) more immersive; however, accessibility gaps persist—particularly for learners with disabilities. A preliminary study involving 30 students and four tutors ($N = 34$) confirmed that the DALverse increases motivation and participation, yet revealed barriers for students with disabilities, highlighting the need for inclusive refinements. *Goal.* This study aimed to (i) evaluate the usability of the DALverse as a collaborative environment and (ii) assess whether animated avatars with gestures enhance communication between hearing and deaf participants in DE contexts. *Method.* A three-stage sequential design was adopted: (1) An exploratory observational study to inform the refinement of the DALverse design; (2) Pilot Experiment with three hearing participants, focused on gesture usability and technical robustness; and (3) Main Experiment with five deaf participants, centered on communicative clarity of animated gestures. The sessions included collaborative tasks on a digital whiteboard and application of the System Usability Scale (SUS), along with qualitative analysis of participant feedback. *Results.* Pilot Experiment reached an average SUS score of 92.5, rated as “Excellent”, indicating high participant acceptance. Main Experiment achieved a SUS score of 62.0 (“Acceptable”), reflecting the impact of latency and the absence of some gesture features. Nonetheless, deaf participants reported autonomy in navigation, communicative richness, and unanimous preference for DALverse as a means of interaction. *Conclusion.* Within the scope of this small case study, the combination of chat, voice, and gestural avatars in DALverse was perceived by participants as supporting engagement and collaboration in DE, including among deaf participants. These findings should be interpreted cautiously given the limited sample sizes and the primarily qualitative nature of the evidence. However, the moderate usability observed in the group with disabilities underscores the need to expand the gesture repertoire aligned with Brazilian Sign Language (Libras), incorporate facial expressions, and optimize graphical performance. These enhancements are essential to transform the metaverse into an inclusive and scalable educational tool.

Keywords: Educational Metaverse, Human-Computer Interaction, Accessibility, Gestural Avatars, Distance Education

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1 Introduction

The COVID-19 pandemic accelerated digital transformation in education, reinforcing the need for more accessible and inclusive Distance Learning (DL) environments [Radianti *et al.*, 2020; Tlili *et al.*, 2022; Lin *et al.*, 2022]. In this context, Virtual Learning Environments (VLEs) have increasingly incorporated interactive and immersive technologies aimed at improving the learning experience, including for students with disabilities [Damasceno *et al.*, 2024a]. Although several metaverse and virtual learning platforms have been explored in the literature, such as VoRtex [Jovanović *et al.*, 2022], Vircadia [Vircadia Project, 2024], and Sansar [Sansar Inc., 2024]. This study does not position Dell Accessible Learning (DAL)/DALverse as the state of the art. Instead, the DAL platform was selected as a case study due to its explicit accessibility focus and the researchers’ facilitated access to its development environment, enabling controlled experimentation and iterative refinement.

Building on the inclusive approach that guided the choice of the DAL platform, this study aims to investigate how the

metaverse can foster collaborative interactions between deaf and hearing participants in educational settings. The DAL platform was deemed appropriate for this purpose due to its design focus on inclusive Distance Education (DE). However, the conceptual framework developed in this study can be adapted to other platforms that follow similar accessibility guidelines [Damasceno *et al.*, 2024b]. While there are existing initiatives that seek to integrate theory and practice in DL through innovative technologies [Damasceno *et al.*, 2020, 2022], a gap remains regarding the use of more immersive solutions, particularly those involving Assistive Technologies (ATs) that can enhance participation and equity in educational processes.

In this context, the metaverse emerges as a promising disruptive technology, capable of expanding the possibilities of educational interaction by simulating real-world actions in virtual environments [Davis *et al.*, 2009]. According to Lin *et al.* [2022], the advancement of digital transformation has intensified the use of the metaverse in education, aiming to make the teaching and learning process more accessible and

engaging. Thus, integrating the metaverse with ATs strengthens this inclusive proposal, aligning with the guidelines of the Brazilian Ministry of Education regarding the adoption of pedagogical practices that are integrated and centered on diversity [Kye *et al.*, 2021]. Considering the potential of the metaverse when combined with ATs, Damasceno *et al.* [2024b] point out that students with hearing impairments still face barriers to collaborative participation in DL. These difficulties stem from the accessibility limitations observed in current WebGL¹-based metaverse platforms, such as limited facial rigging, restricted real-time lighting, and simplified physics, which compromise equity in interactions and hinder engagement in collaborative educational practices. In this scenario, a metaverse-based platform can provide a more inclusive and collaborative environment, especially as collaboration is considered essential for learning and integration within communities.

Aiming to investigate the inclusion of people with hearing disabilities in immersive environments, this study began with an exploratory investigation into the behavior of deaf participants in educational contexts within the metaverse. As a result, it became essential to analyze how communication can be facilitated, particularly in situations where collaboration is fundamental for learning. Accordingly, this study is guided by the following **central research question**: *How can deaf learners interact naturally and collaboratively in a metaverse-based educational environment, relying on predefined gestural avatars rather than continually depending on an interpreter?*

To address this question, two empirical studies were conducted. The first, a Pilot Experiment with hearing participants, examined usability, engagement, and the technical stability of the platform. The second experiment involved deaf participants and a tutor (representing the hearing participant) and investigated communicative effectiveness, perceived autonomy, and the extent to which predefined semantic gestures support inclusive collaboration. Together, these studies provide empirical evidence on how metaverse-based interaction can facilitate accessible and equitable collaboration between deaf and hearing learners.

One of the main challenges was identifying and mapping key behaviors that could be incorporated into avatars to support communication and interaction among participants. Based on this analysis, the research focused on implementing these behaviors into animated avatars, with the aim of fostering collaborative interactions between deaf and hearing participants in metaverse-based educational environments.

This work contributes at three complementary levels. First, it proposes and documents the iterative design of gestural avatars for deaf-hearing collaboration in educational metaverses. Second, it presents practical technical adaptations for implementing accessible avatar-mediated interaction within a browser-based WebGL environment. Third, it provides empirical evidence from exploratory, pilot, and main experiments involving deaf and hearing participants, analyzing usability, communicative support, and collaborative interaction in DALverse.

Finally, in addition to this introductory section, the paper is organized as follows: Section 2 presents the fundamental concepts that support the research, while Section 3 describes the adopted methodological approach. Section 4 details the process of creating the animated avatars, and Section 5 introduces the case study used as the basis for the experiments. In Section 6, the experimental design developed to examine the potential of DALverse as an inclusive DL environment is described. Section 7 presents the discussion and analysis of the results obtained, along with their respective analyses, and Section 8 discusses the main threats to the study's validity, as well as the strategies proposed to mitigate them. Section 9 outlines the practical and scientific implications drawn from the findings. Finally, Section 10 presents the final remarks and suggestions for future work.

2 Background

This section presents the key concepts related to educational metaverses, accessibility, and Human-Computer Interaction (HCI). Previous works on inclusive virtual environments, gestural avatars, and usability guidelines for people with hearing impairments are discussed, providing the theoretical foundation for the DALverse artifact.

2.1 Metaverse in education

Lin *et al.* [2022] explore the integration of traditional education with Web 2.0 resources through Massive Open Online Courses (MOOCs), highlighting limitations such as the lack of engaging content and low student participation. With the imminent arrival of Generation Z, already accustomed to online education, it becomes necessary to rethink educational models and prepare them for a new transformation. In this context, the metaverse emerges as a promising alternative by offering greater interactivity, authenticity, and immersive experiences. According to Fernandes and Werner [2022], the metaverse represents a new paradigm in development, in which social platforms based on immersive virtual reality tend to integrate with various types of educational applications.

The metaverse provides an interoperable environment that fosters interaction, student motivation, and engagement in collaborative activities. It differs from traditional VLEs in the way avatars communicate, interact with each other, and manipulate resources and objects within the virtual space. In addition to integrating classical functionalities such as chats, forums, assessments, and virtual libraries, the metaverse transforms the educational experience by making interactions more playful and engaging, which positively impacts student motivation [de Classe *et al.*, 2023]. In this context, students can interact with teachers and peers through their avatars, experiencing a more immersive and meaningful learning process [Tlili *et al.*, 2022].

Thus, metaverse applications are relevant tools for the inclusion of People with Disabilities (PwD). Ball [2020] emphasizes the importance of ensuring that the metaverse is accessible to this audience, recognizing their role as active participants in these environments. However, the author does not specify the types of disabilities nor detail how accessibility and inclusion should be implemented. In this regard, the concept of ATs becomes central, as it encompasses products, services, and strategies aimed at both informational and

¹WebGL: <https://www.khronos.org/webgl/>

physical accessibility, expanding opportunities for PwD to participate in digital environments [Vianna and Pinto, 2017].

2.2 Assistive technology

Assistive Technologies play a fundamental role in the daily functioning of VLEs, fostering educational transformations [Palomino *et al.*, 2025]. The integration of information technology into education has been essential for expanding access and participation for students, regardless of their abilities or limitations [Rodrigues *et al.*, 2025]. The term refers to a set of resources and services designed to provide or enhance the functional abilities of PwD, promoting their autonomy and social inclusion [Bersch, 2008]. The enhancement of these functional capabilities reveals a meaningful intersection with the field of HCI, highlighting the importance of investigating how these two domains can be interconnected to strengthen more inclusive educational practices.

2.3 Human-computer interaction

Investigating how people communicate and collaborate in work, social life, and daily routines is essential to understanding the role of technologies in mediating these interactions. Advances in communication technologies have transformed the ways participants live, stay in touch, build friendships, and organize social networks. Rogers *et al.* [2013] introduce the concept of telepresence, referring to the development of technologies capable of making a person feel present, or conveying a sense of presence, in another location. The authors also highlight the potential of shareable technologies to support new forms of interaction, particularly those aimed at collaboration. This context is relevant to the present study, as it aligns with the theory of embodied behavior [Rogers *et al.*, 2013], which emphasizes the role of the body and physical presence in shaping interactive experiences.

To ensure a natural flow of conversation, people rely on various cues to indicate how long they intend to speak and what they will address (e.g., a speaker may emit subtle signals to mark the end of their turn). These cues include expressions such as “a-ha” or “hmms”, body movements (e.g., moving closer or stepping back), gaze direction (e.g., making or avoiding eye contact), and gestures (e.g., raising a hand), often combined to signal turn-taking transitions. Non-verbal communication plays an essential role in these interactions, encompassing not only gestures and facial expressions but also vocal intonation and other forms of body language [Rogers *et al.*, 2013]. These elements are central to the theory of embodied behavior, which integrates the body and expression into communication and cognition.

The concept of co-presence is central to this study, as it helps to understand the sense of physical presence during interactions with avatars in the metaverse [Rogers *et al.*, 2013]. According to Rogers *et al.* [2013], various shareable interfaces have been developed for simultaneous use by multiple participants, aiming to foster collaboration among co-located groups and promote effective interactions in work, learning, and social contexts.

Beyond usability and user experience as traditionally defined in HCI, accessibility in immersive learning environments also depends on how communication and collaboration are supported in real time, especially for learners who rely on

non-verbal and multimodal interaction.

2.4 Accessibility and non-verbal communication in educational metaverses

Accessibility in educational metaverses is not limited to interface-level accommodations. It also depends on how immersive environments support shared understanding, communication, and coordination during collaborative activities. Prior research on immersive learning and metaverse-based education highlights both the potential of immersive collaboration and the challenges related to inclusive and accessible design, particularly for learners with disabilities [Radiani *et al.*, 2020; Tlili *et al.*, 2022]. From a HCI perspective, embodied behaviors of avatars, such as gestures and expressive cues, can function as grounding mechanisms that support meaning-making and co-presence, especially for deaf learners, by enabling the monitoring of attention, intentions, and interactional cues in VLEs [Damasceno *et al.*, 2024b].

For deaf learners, accessibility challenges in educational metaverses are closely related to communication barriers rather than to navigation or content presentation alone. Prior work on metaverse-based learning environments highlights the role of avatar-mediated interaction and social presence in supporting collaborative activities [Lin *et al.*, 2022]. From an accessibility and HCI perspective, non-verbal avatar behaviors, such as gestures and facial expressions, can support pragmatic interaction functions that are central to collaborative learning, including turn-taking, clarification, agreement, and shared grounding, operating as assistive communication resources for deaf learners [Damasceno *et al.*, 2024b].

Despite growing interest in educational metaverses, systematic approaches that explicitly connect accessibility requirements, avatar-mediated non-verbal communication, and DE remain limited. To address this gap, we adopt the Metaverse4Deaf conceptual framework [Damasceno *et al.*, 2024b] as a theoretical foundation. Metaverse4Deaf emphasizes that inclusive metaverse-based distance education for people with hearing impairments should integrate assistive communication mechanisms, embodied avatar behaviors, and iterative user-centered refinement. Rather than aiming to replace interpreters, this perspective seeks to increase learners' autonomy and communicative control by enabling richer, more direct avatar-mediated interaction in collaborative educational scenarios.

Given the central role of avatar expressiveness for accessibility and communication in metaverse-based learning, the following section summarizes the virtual avatar production process and motivates the adaptations adopted in this work.

2.5 Virtual avatar production process

A virtual avatar is a digital representation of a human being whose production involves art, design, and computational techniques. One of the main challenges in this process is avoiding the “uncanny valley” [Mori *et al.*, 2012], in which near-human characters evoke discomfort due to imperfections such as stiff expressions or unnatural gestures. This issue is especially critical in Brazilian Sign Language (Libras), where facial and bodily expressions carry grammatical, affective, and discourse functions [Xavier, 2017].

Although there are tools and characters capable of performing signs in Libras, such as VLibras, HandTalk, and ProDeaf, studies such as Vieira *et al.* [2014] show persistent limitations related to fluency, naturalness, and identity representation.

Avatar creation traditionally follows a workflow that resembles the game development pipeline described by Beane [2012], divided into pre-production, production, and post-production:

1. Pre-production: definition of the character concept, visual references, and briefing [Caivano *et al.*, 2008].
2. Production: execution of stages such as 3D modeling, retopology, UV mapping, texturing, rigging (skeleton creation), and animation.
3. Post-production: integration of the animated character into an interactive platform, where states, transitions, and behaviors are programmed.

This pipeline represents the full professional workflow for building avatars from scratch. However, real-world projects often adapt or simplify this process depending on constraints such as available tools, team size, required fidelity, and platform limitations.

Although **Figure 1** is presented as a sequential pipeline for clarity, each phase is inherently iterative. Adjustments in modeling, rigging, texturing, or animation frequently require returning to previous stages. Therefore, the workflow should be understood as a flexible, feedback oriented process, rather than a rigid linear model, which serves as the theoretical reference for the adaptations described in Section 4.

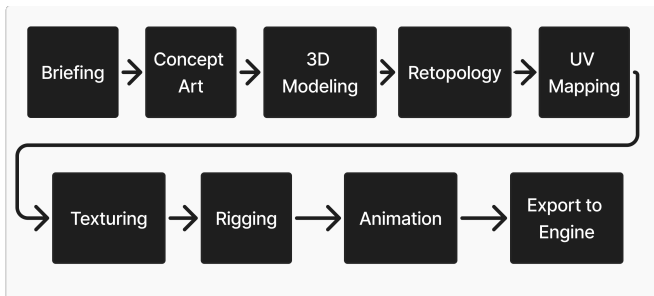


Figure 1. Flow chart illustrating the high-level 3D avatar production pipeline. Although presented sequentially for clarity, each stage is iterative and may require returning to previous steps for corrections and adjustments.

3 Methodology

This section describes the procedures adopted for the planning and execution of the study. It details the use of participatory design, the development stages of the artifact, the selection of evaluation instruments, and the overall design of the experiments conducted with participants.

Starting with a **literature review**, conducted with the aim of gathering, organizing, and analyzing evidence on the metaverse, AT, and DE [Damasceno *et al.*, 2023]. For this purpose, the Rapid Review (RR) methodology was adopted [Cartaxo *et al.*, 2018], chosen for its cost-effectiveness, focus on specific evidence, and close collaboration with professionals. This approach proved suitable for the context, given that some of the authors work in a company focused on developing accessible and innovative solutions for DE and AT.

3.1 Findings from the rapid review

The RR reported in Damasceno *et al.* [2023] was conducted prior to the empirical study described in this paper and served as a foundation for defining the design goals of DALverse and the present experiments. That review was guided by the following questions: (RRQ1): How have primary studies on educational metaverses and accessibility evolved over the years?; (RRQ2): Which domains of accessibility in DE have been explored in the context of metaverse-based platforms, and how do these studies approach the topic?; (RRQ3): What challenges have been reported in implementing accessibility in educational metaverse platforms?; and (RRQ4): Which strategies and methodological approaches have been adopted to evaluate accessibility and inclusion in such environments?

The results of this RR indicated that most proposals (57%) were published in scientific journals between 2020 and 2023, with 42.5% focusing on Chemistry laboratories. Evaluative research predominated (57.1%), while empirical experiments and mixed quantitative–qualitative methods were applied in 42.8% and 71.4% of the studies, respectively. The main challenges identified include instrumentation, technical issues, system complexity, student performance, sense of presence, and accessibility assessment. Based on these findings, an Evidence Report was developed [Damasceno *et al.*, 2023] to guide the design of DALverse and to inform the **central research question** of the present empirical study.

3.2 Related work

The reviewed studies examined the relationship between the metaverse and education [Alfaisal *et al.*, 2022; Onggirawan *et al.*, 2023], as well as between the metaverse and accessibility [Fernandes and Werner, 2022]. Unlike these works, our review considered all three pillars together, aiming to understand how accessibility is being addressed in DE environments based on the metaverse. Furthermore, we identified open challenges in meeting the perceptions of professionals in real-world and providing support to researchers, outlining research opportunities that may contribute to assisting PwD.

Previous work by the authors has already examined motivation, perceived learning, and collaborative interaction in metaverse-based DE through a quasi-experiment involving 34 learners [Damasceno *et al.*, 2025]. The findings of that study provided initial empirical implications for the design of DALverse, which informed the subsequent stages of development reported in the present paper.

3.3 Exploratory experiment

This study analyzed the interaction between deaf and hearing participants in collaborative educational activities, aiming to adapt such dynamics to more inclusive virtual environments. Interviews were conducted with DELL collaborators to understand the use of digital technologies and identify requirements for improving the DALverse artifact.

The usability evaluation was planned to occur throughout the design process, adopting a formative approach that allows iterative adjustments before finalizing the system, as suggested by Rogers *et al.* [2013] and Barbosa *et al.* [2021]. Active user participation was essential in this process, with the participatory design method adopted as a central strategy for

experiment development [Nielsen, 1994], see **Figure 2**.



Figure 2. Collaborative interaction between deaf and hearing participants with annotations and recordings

The study employed an observational experiment during a collaborative activity involving a physical whiteboard, complemented by focus group sessions conducted both in-person and within the DALverse environment (see **Figure 2** and **Figure 3**). The exploratory observational experiment was conducted in a physical classroom before the full implementation of DALverse. At this stage, participants used traditional DL materials and a physical whiteboard, and an early prototype of DALverse was presented solely for feedback collection. Participants completed three tasks: (i) watching an online video lesson on agile methodology; (ii) collaboratively representing the project constraint triangle on a physical whiteboard; and (iii) collaboratively outlining the stages of the waterfall model on the whiteboard. Because DALverse was still only a functional prototype, it was later presented in a focus group session in which deaf and hearing participants discussed communication barriers, accessibility considerations, and suggestions for improvement. This feedback informed subsequent design decisions, including the definition of gestures, interaction flows, and collaborative features incorporated into the final version of DALverse.

A blue post-test questionnaire² was administered to gather participant feedback. The methodology included screen captures, video recordings, and researchers' field notes, along with participants' perceptions and suggestions shared during the sessions (see **Figure 2**). This qualitative approach revealed factors that influenced the user experience, providing insights into collaborative interaction and system usability. The main goal was to support the development of natural and effective interactions within the metaverse, tailored to the communication needs of deaf participants. Observations from the physical environment informed enhancements in communication and inclusion within virtual educational settings.

The class viewing phase on the web began after the pre-test questionnaire. Deaf and hearing participants attended the lessons of the course "Agile Methodology for Software Development" on the DAL platform. Hearing participants used modes suited to their profiles, while deaf participants were supported by sign language interpreters. During the experiment, interactions on the physical whiteboard were recorded through screenshots and video, with participants' consent. These recordings enabled an analysis of the collaborative activities performed on the shared whiteboard, facilitating the identification and cataloging of gestures used in



Figure 3. Focus group with researcher and deaf and hearing participants.

communication between deaf and hearing participants during the tasks.

Figure 4 summarizes the observed gestures, highlighting both the effectiveness and challenges encountered in mixed communication, and demonstrating how these gestures contributed to collaboration and mutual understanding among participants. Faces were blurred to protect the identity of the research subjects. This analysis is essential for enhancing future interactions in the DALverse virtual environment, particularly in the implementation of more intuitive and effective avatars and gestures. More than 30 gestures were observed³.

Regarding the linguistic analysis, the observational experiment that identified 31 gestures used in interactions between deaf and hearing participants, without the mediation of a sign language interpreter, represents a significant finding for gesture linguistics and its practical applications in collaborative communication environments, particularly in educational contexts and the metaverse. The results were analyzed in light of the theories and approaches proposed by Adam Kendon [Kendon, 2004] and David McNeill [McNeill, 1992], who explore the integration of gestures and language in meaning-making during social interaction. These theoretical contributions help to understand how the observed gestures function not only as support for speech or signing but also as central elements in constructing mutual understanding among participants with different communication modes.

The design of DALverse was informed both by prior evidence from a RR on metaverses, ATs, and DE [Damasceno et al., 2023] and by participatory feedback collected during the exploratory experiment. In particular, the focus group with deaf and hearing participants allowed us to identify concrete accessibility barriers and communication needs, which were subsequently translated into design requirements for the gestural avatars, the collaborative whiteboard, and the overall interaction flow. Although we do not frame this process as a formal participatory design methodology, these iterative cycles of feedback and refinement ensured that representatives of the target audience actively contributed to shaping the environment prior to the Pilot and Main Experiments.

The findings guided the implementation of gestures and facial expressions in the avatars, aiming to enhance communication and make interactions more natural and inclusive, especially between deaf and hearing participants. In addition, new avatars were developed with customization options, allowing learners to adjust their avatars' appearance and behavior according to personal preferences. These improvements are intended to increase learner engagement and immersion within the virtual environment.

²Post-test questionnaire: <https://bit.ly/Pos--test-JIS-2025>

³Gestures Identified: <https://bit.ly/Gestures-JIS-2025>

Gestures	Description
	Place the index finger on the side of the head (indicating the idea of "do you remember?")
	Rotate the hand and end with palm up (suggesting the idea of "is this it?")
	Head movements (suggesting yes, agreement)
	Oscillating index finger and pointing (indicating "continue")
	Two palms down, crossing (suggesting "finished, done")

Figure 4. Gestures in Interaction Between Deaf and Hearing Participants

Because this stage aimed at requirements elicitation and gesture cataloging in mixed deaf-hearing interaction, the subsequent evaluation stages were organized sequentially: first, a non-disabled pilot as a robustness filter and only then the main study with deaf participants and the hearing role represented by a tutor avatar.

3.4 Experiments with animated avatars

To examine the potential of DALverse as an inclusive DL environment, we conducted two experiments, based on the conceptual framework of [Damasceno et al., 2024b] (gaining insights into the implementation and evaluation of an educational metaverse focused on accessibility for deaf participants), both based on animated avatars that enable gestural communication within the metaverse. We first evaluated DALverse with non-disabled participants (Pilot Experiment) to establish a "robustness filter": if the platform showed usability barriers or a lack of engagement even among participants without specific needs, it would likely present even greater challenges for deaf participants.

This pilot trial allowed us to: (i) verify technical stability (that is, ensuring stable frame rate, absence of crashes, correct synchronization of avatars between clients, and reliable triggering of gesture animations during multi-user interaction), (ii) identify potential initial resistance, and (iii) adjust the environment before moving forward. Only after confirming that the system operated in a satisfactory and engaging manner with the non-disabled pilot group did we conduct a Main Experiment with deaf participants and one hearing tutor, whose communicative complexity is greater. This sequential

approach reduces bias, avoids overburdening participants with disabilities in premature tests, and ensures that any difficulties observed in the second experiment can be attributed mainly to specific accessibility demands rather than basic technological flaws.

No sensitive or personally identifiable data from participants was collected or analyzed. All information regarding the purpose of the research was clearly presented, and informed consent was documented through a Free and Informed Consent Form (FICF), provided at the beginning of the data collection questionnaire. The study received ethical approval from a human research ethics committee under the **Certificate of Presentation for Ethical Consideration (CAAE)** number 81662224.6.0000.5534. This code is issued by the Plataforma Brasil to identify research projects submitted to the CEP/Conep system for ethical review.

In another preliminary study, as discussed in Damasceno et al. [2025], the DALverse as an inclusive learning environment for DE was investigated. Thirty students and four tutors from the course Agile Methodologies for Software Development, offered on the DAL platform, participated in the study. The experimental design focused on two main goals: (i) evaluating the use of the metaverse as a collaborative learning space, and (ii) measuring the motivation such an environment can generate among students. Participants explored DALverse autonomously, engaged in collaborative activities, and completed questionnaires on usability perception and engagement at the end of the session. The results indicated high levels of motivation and participation, suggesting that the metaverse positively contributes to the pedagogical dynamics in DE. However, accessibility challenges also emerged, particularly for students with disabilities, highlighting the need for improvements in adaptive resources and the user interface [Damasceno et al., 2025].

These findings support the improvements described in the present research and reinforce the importance of ensuring full inclusion in future implementations of DALverse. The collected data can be accessed at the following link⁴. The data related to the experience reports from Pilot Experiment⁵ and Main Experiment⁶ were also stored in Google Sheets. In this paper, glosses are used to represent signs from Libras, following the convention of writing each sign in uppercase Portuguese. These glosses are not literal translations, but symbolic representations of signs.

3.5 Open science and data availability

In alignment with open science principles and with the policies of the Journal of Interactive Systems, all datasets and study materials used in this research have been made publicly available to ensure transparency and reproducibility. The shared resources include anonymized datasets, interaction logs, gestural data, experience reports, briefing materials, and other raw data collected across the Exploratory, Pilot, and Main Experiments.

To make access easier and more stable, all URLs were converted into short permanent links. A complete list of datasets and materials, along with their respective access

⁴RawData:<https://tinyurl.com/DadosBrutosJIS2025>

⁵NoPwDRReport:<https://tinyurl.com/RelatosNaoPcDJIS2025>

⁶PwDRReport: <https://bit.ly/Relatos-PcD-JIS-2025>

links, is provided in Appendix A. Researchers and practitioners are encouraged to explore and reuse these materials in accordance with ethical guidelines.

4 Designing Animated Avatars for Both Hearing and Deaf Learners

This section explains the adapted pipeline effectively used to create the animated avatars in DALverse. Although subsection 2.5 presents the conventional virtual character production workflow as a theoretical reference, the development did not follow the complete pipeline. Instead, we adopted a reduced and pragmatic version of it, constrained by:

1. The use of a small interdisciplinary team,
2. Limited development time,
3. Performance restrictions of a browser-based WebGL platform,
4. The lack of avatars natively designed for sign-language communication.

The adopted workflow consisted of:

1. Defining functional and accessibility requirements;
2. Selecting pre-existing 3D avatars from Mixamo⁷;
3. Recoloring textures and applying light customization;
4. Modifying and extending the rig to support Libras gestures;
5. Manually animating prioritized signs in Blender⁸;
6. And integrating these animations into the DALverse metaverse.

To ensure access to the virtual environment, the metaverse was implemented using the Babylon.js library⁹, which allows it to run directly in the browser without requiring installation. This decision promotes accessibility but imposes performance constraints, making it necessary to optimize the 3D models—both avatars and environments—in terms of polygon count and texture image resolution. These simplifications aimed to ensure compatibility with computers of varying graphical capabilities, considering that part of the target audience might use devices with hardware limitations.

4.1 Environment

Although the focus of this section is avatar development, a brief contextualization of the virtual environment is necessary, as its spatial and technical constraints directly influenced the design decisions reported in the experiments. This stage of environment creation considered spatial representativeness to provide learners with an experience closer to their real-life context. The design was inspired by urban spaces familiar to students, aiming to facilitate orientation and foster a sense of belonging. The scene was built with capacity for up to 30 simultaneous participants, reflecting the average class size in online courses, and included a central whiteboard placed on a stage to highlight the teacher or tutor avatar during explanations.

Visual elements such as trees and vegetation were initially incorporated to enrich the environment; however, the

need to ensure smooth performance in the browser required reducing both the quantity and resolution of these elements, due to their significant impact on processing. A critical issue observed during testing was the lack of interactivity in furniture objects such as chairs and tables. Although these items were visually present in the space, participants reported frustration at not being able to interact with them, for example, by sitting on the chairs. This highlights the importance of aligning visual design with expected interactive functionality, especially in educational environments that aim to be immersive.

The configuration of lighting in the virtual environment represented one of the main technical challenges faced during the development of the platform, especially due to the decision to use Babylon.js, a WebGL-based library that runs directly in the browser. While this choice enhances accessibility and eliminates the need for additional installations, it also imposes significant limitations on the use of advanced visual effects, particularly with regard to the realistic simulation of lighting and shadows.

Unlike graphics engines based on offline rendering or ray tracing, which enable the use of global illumination, soft shadows, volumetric lighting, and dynamic reflections—Babylon.js relies primarily on simplified real-time techniques, such as hemispheric, directional, and point lights. Shadow rendering, for instance, requires the generation of shadow maps, the quality of which is directly tied to the learner's GPU capacity. Since the project was designed to be accessible to a broad audience with varying levels of computational power, lightweight configurations were prioritized, including a reduced number of light sources and the absence of real-time shadows on secondary elements.

This decision resulted in a functional environment but with a limited level of visual fidelity. From the designer's perspective, this aspect was recognized as a trade-off in which realism had to be sacrificed in favor of performance. As a result, the final lighting configuration did not fully match the initial aesthetic vision, as illustrated in **Figure 5**. Nevertheless, it ensured smooth navigation and compatibility with lower-end machines, maintaining the environment's accessibility without compromising its core purpose: supporting interaction and learning in Brazilian Libras.

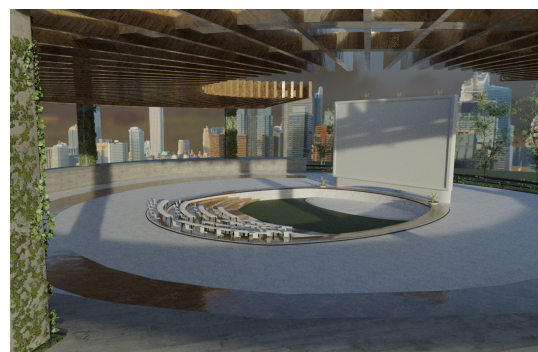


Figure 5. Render of the auditorium used in the metaverse

4.2 Requirements definition (briefing)

The initial stage consisted of developing a simplified functional briefing, created collaboratively with the pedagogical

⁷Mixamo: <https://www.mixamo.com/#/>

⁸Blender: <https://www.blender.org/>

⁹Babylon: <https://www.babylonjs.com/>

and technical teams. This document consolidated essential high-level requirements regarding the target audience (Deaf adult learners with varying experience in educational technologies), platform visual guidelines, and usage context (immersive classroom). The briefing also considered the communicative goals of the avatar, drawing from international guidelines that recommend best practices for presenting content in sign language, such as visual contrast between the character and background, realistic human proportions, and gesture clarity (ISO/IEC No. 20071–23:2018). Although the project did not follow all traditional steps, mentioned at subsection 2.5, such as concept art and modeling from scratch, the briefing guided key decisions on avatar selection of third party companies, customization, and gesture validation.

4.3 Avatar selection

As discussed in the theoretical framework, early studies demonstrated that learners tend to react to virtual agents in socially meaningful ways, similar to interactions with other people [Reeves and Nass, 1996]. More recent research in immersive and educational virtual environments reinforces this perspective, showing that perceptions of social presence, engagement, and interaction quality are intensified in VR and metaverse-based systems [Radianti et al., 2020]. These social expectations include aspects such as response time, communication fluency, and coherence in nonverbal behavior. For instance, when a virtual system takes too long to respond to a question, the delay is often perceived as longer than it would be in a human conversation, leading to frustration or a sense of inefficiency. Consequently, careful attention to movement naturalness, action clarity, and avatar expressiveness becomes essential. In the case of Libras, these requirements are even more critical, as communication relies on precise gestures, coherent body posture, and facial expressions with grammatical value [Xavier, 2017].

Given this context, the project sought a solution that balanced technical feasibility and communicative effectiveness, despite constraints on time and resources. The adoption of pre-built models from the Mixamo.com library (an Adobe platform) was a strategic decision: it allowed the to focus efforts on customizing and animating the Libras signs, even though it introduced expressive limitations which, as noted by Mori et al. [2012], may contribute to the emergence of the phenomenon known as the uncanny valley.

As part of the process of adapting avatars to the educational context, care was taken to provide basic visual customization features, enabling differentiation between characters representing students, teachers, and other participants. This visual distinction is especially relevant in immersive environments, where quickly identifying interlocutors supports the organization of interactions and the recognition of social roles within the virtual classroom [Daly and Reitmayr, 2018]. Additionally, ensuring that avatars are not excessively similar helps reduce the sense of artificiality or repetition, contributing to a more natural and personalized experience. Variations in clothing colors, skin tones, and small accessories were selected as technically feasible solutions within the limitations of the Mixamo library, following guidelines proposed by ISO/IEC standard n° 20071–23:2018, which recommends contrast between signers and background,

visual neutrality, and gestural clarity for sign language content.

Male and female profiles were selected from the Mixamo library in an effort to represent student and teacher personas with more formal clothing, as shown in **Figure 6**, prioritizing models that met minimum functionality and expressiveness criteria. However, most commercially available avatars were not designed for Libras interactions or detailed non-verbal communication, featuring simplified meshes and rigs poorly suited for complex facial and hand movements. Therefore, the selection process focused on models with hand rigs capable of participant finger articulation and mesh topologies that allowed manual texture adjustments—such as models where the hair is not merged with the body mesh—facilitating later replacement or removal and enabling a degree of visual customization.

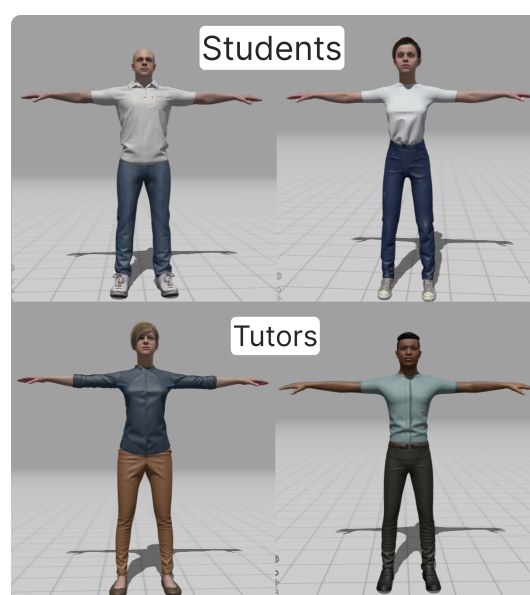


Figure 6. Original models from the Mixamo library used as the base for the project's avatars.

4.4 Texture recoloring and customizations

After selecting the models, the avatars underwent a visual customization stage to reflect the institutional and educational identity of the DALverse platform. The textures were recolored using Adobe Substance¹⁰ software to simulate virtual school uniforms and bring the characters closer to a classroom context. This choice aimed to strengthen learners' identification with the environment, reinforcing their sense of belonging. **Figure 7** shows a screenshot during the painting process of the PNG file used by the model to cover its surface.

In addition, the project aimed to promote ethnic-racial representation and body diversity through variations in skin tones, hairstyles, and customized visual elements. However, this stage faced technical limitations: some models featured inaccurate UV mappings, which hindered the clean and precise application of textures. As a result, manual adjustments were required in Blender, including UV remapping of the 3D mesh.

¹⁰www.adobe.com/br/products/substance3d/apps/painter.html



Figure 7. Final texture map and the 3D model on the right.

4.5 Animation and integration

The challenge of finding characters with functional facial rigging proved especially critical, as Libras heavily relies on facial expressions and eye movements to convey grammatical and emotional nuances [Xavier, 2017]. The lack of avatars specifically designed for signed communication in the market highlighted a technical gap and reinforced the need for careful adaptations. Although the models from the Mixamo library include a basic skeletal structure (rig) suitable for generic animations, their application in contexts requiring gestural precision and expressiveness, such as the Libras, demands additional adjustments to ensure naturalness and clarity in communication.

The standard Mixamo rig provides a basic bone hierarchy with deformers for limbs and fingers, but lacks auxiliary controllers, facial rigging, and offers limited pose organization and control. In light of these constraints, technical modifications were carried out on the rig to enhance its responsiveness to the linguistic and expressive demands of Libras. The main adjustments performed are described below:

Addition of finger controllers: Although phalange bones were present, it was necessary to add auxiliary bones (control bones) and organize them into structures that enabled more precise manual animations—an essential requirement for the legibility of sign language gestures. **Implementation of hybrid IK/FK systems:** Arms and legs were adapted to support inverse kinematics (IK) for body positioning, which facilitates the creation of stable postures and smoother gestures.

1. **Simplified facial rig:** Since the original rig lacked facial bones, shape keys or control bones were introduced to support basic expressions such as eyebrow movement, eye direction, and mouth shapes, in alignment with the grammatical importance of facial expressions in Libras [Xavier, 2017].
2. **Pivot and rotation axis adjustments:** Bone rotation axes, particularly in the hands, were corrected to ensure smooth animation curves and to prevent undesired locking or mesh deformations.
3. **Weight painting refinement:** The automatic deformations generated by Mixamo were reviewed, and critical areas—such as shoulders, elbows, and finger joints—received new weight painting to preserve volume and anatomical proportions during movement.
4. **Drivers and constraints for facilitated animation:** drivers and constraints were applied to allow groups of bones (such as all the fingers of a hand) to be controlled by a single controller, optimizing the animation process

and reducing pose errors.

5. **Adaptation for retargeting and Unity¹¹ integration:** The final rig was reorganized with standardized naming conventions and a structure compatible with retargeting systems and Unity's animation framework. This allowed sign gestures to be integrated into a state machine and triggered dynamically based on learner commands.

With the avatars finalized, the animation stage for the Libras signs began using the Blender software. The first step involved adapting the hand and arm rigging to allow greater control over articulated movements, a critical requirement for producing intelligible signs. Gesture legibility was treated as a priority, given that the clarity of signing directly impacts message comprehension and learner confidence. In Figure 8, the character's rig adapted for Blender is shown on the left, with the controllers visible over the model on the right.

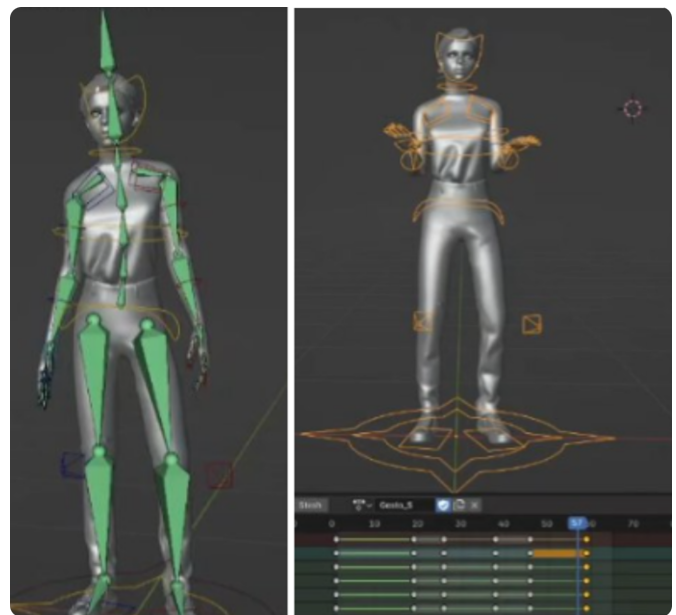


Figure 8. Rig of the model and control handles

More than 30 signs were mapped based on reference videos, prioritizing high-frequency gestures commonly used in educational contexts. The selection and validation of these signs were supported by a Libras interpreter, who contributed both to identifying the most representative signs and verifying the precision and coherence of the movements. However, one of the main challenges faced was the limitation in synchronizing manual gestures with facial expressions, a fundamental component of Libras grammar. This difficulty stems from the fact that models in the Mixamo library do not offer detailed facial rigs with control over specific facial muscles. Despite acknowledging the importance of this limitation, it was decided not to implement a full facial rig system at this stage of the project, due to the significant increase in technical complexity and development time it would entail—which would exceed the boundaries initially defined in the project scope.

The finalized animations were saved in a local database and linked to commands triggered within the DALverse platform. Each command, such as “open room”, “answer”, or “ask”, activates a predefined sequence of movements that are

¹¹Unity: <https://unity.com/pt>

rendered in real time within the immersive environment. Although the level of expressiveness does not yet reach the full complexity of Libras, initial tests demonstrated that, even with limited resources, avatars exhibiting clear gestures and engaged posture foster greater engagement among deaf participants when compared to static or purely textual avatars [Mori et al., 2012] [Xavier, 2017].

5 DAL Platform

This section contextualizes the DAL environment and its practical application in DL courses. It presents the platform's available features, the types of learners involved, and the DALverse's role as an immersive and accessible extension for educational interactions between deaf and hearing participants.

This case study is framed within the principles of Computer-Supported Collaborative Learning (CSCL), as it examines how deaf and hearing participants coordinate actions, co-create visual artifacts, and negotiate meaning in a shared virtual space. Rather than focusing solely on participant usability, the analysis emphasizes collaborative dynamics such as turn-taking, synchronous editing of shared artifacts, and multimodal communication—which are central to CSCL approaches. This framing helps position DALverse not only as a technological solution, but as a learning environment designed to mediate collaboration and joint problem-solving.

The DL platform, known as DAL [de MB Oliveira et al., 2016], was selected as the experimental environment for applying the proposed approach. The choice of this platform was motivated by both methodological and academic factors. From a methodological standpoint, some of the researchers are institutionally affiliated with the DAL Development and Innovation Laboratory, which facilitated access to the experimental environment and supported the controlled implementation and validation of the proposed approach. From an academic standpoint, DAL has been recognized for its innovative work in digital inclusion and in promoting autonomy for people with disabilities, which aligns directly with the objectives of this research. To mitigate potential biases, however, the study design, data analysis, and interpretation of results were conducted in accordance with an ethics-approved protocol and independently of any commercial interests.

The DALverse is one of the innovations developed by the UECE's development and innovation laboratory [Nascimento et al., 2017], along with other products such as STU-ART [Damasceno et al., 2020]. It integrates the DAL platform, a DL environment designed to enhance accessibility for students with various types of disabilities, including physical, hearing, and visual disabilities [Nascimento et al., 2017]. Upon enrolling in a course on the DAL platform, students gain access to the "Metaverse" room, where they can customize their virtual presence by choosing from three predefined avatar profiles: male, female, or a gender-neutral robot avatar. In this virtual environment, learners can navigate by controlling the avatar's movement using the keyboard arrows and the mouse **Figure 9**.

Each avatar, with the exception of the robot, performs five basic movements: walking, rotating, idling, hand signaling, and directional gliding. The robot, conversely, floats in

four directions (forward, backward, left, right). The system processes and renders these movements, generating realistic motion within the virtual space.

Promoting Inclusion in Education: Fostering inclusive education yields benefits such as social development, empathy, rich environments, collaboration, and mutual understanding. Quek and Oliveira [2013] highlights these advantages by developing a collaborative classroom simulation that features a digital whiteboard, which allows for the use of an eraser, pencil, text, and adjustments for color and size. The tool is used by one participant at a time, while others can request editing privileges via their virtual "tablets", ensuring effective management and a secure environment (see **Figure 10**). Upon gaining access to the digital whiteboard, a learner can share a browser window, an application, or their entire device screen, with or without audio. This feature allows tutors and students to present their work, pose questions, and display other applications from their computers directly on the whiteboard.



Figure 9. DALverse avatar interaction interface

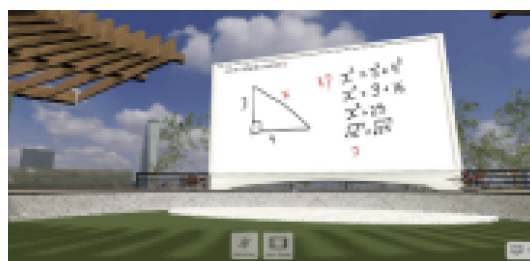


Figure 10. Collaborative whiteboard interaction within DALverse

6 Case Study: Animated Avatar Experiments

This section describes the evaluation process for avatars with Libras-based gestures. It details the tests conducted with hearing and deaf participants, the types of gestures implemented, the validation criteria, and the instruments used for collecting both qualitative and quantitative data.

Use of DAL and DALverse in sequence, in both experiments, participants used two integrated environments in a fixed order. First, they accessed DAL (the LMS) to review the course materials participantly (Agile Methodology for Software Development, including the project constraint triangle and the waterfall model). After this preparation step, they transitioned to DALverse (the metaverse extension of DAL), which was used for the synchronous collaborative phase (e.g., virtual whiteboard activities and peer interaction).

6.1 Pilot Experiment

First phase was the study definition, this study analyzed the use of the metaverse as an inclusive learning environment in DE, focusing on students and alumni without disabilities, and involved 3 students and 1 tutor. It is worth noting that over 30 students were recruited as research subjects; however, the others did not attend. The participants answered questionnaires about usability, learning perception, and motivation. The objective was to analyze the impact of animated gestures in avatars as a communication tool for the deaf in collaborative metaverse environments, with the goal of understanding how these interactions promote collaboration and strengthen inclusion in educational activities.

This decision is consistent with our earlier quasi-experimental study [Damasceno *et al.*, 2025], in which we conducted a broader investigation of motivation and perceived learning in metaverse-based DE. In the present paper, however, our focus shifts specifically to communicative accessibility and gestural interaction for deaf learners.

Second phase was the study planning, that first consisted in the definition and selection of participants. Inclusion and exclusion criteria were established, as detailed below: **Inclusion Criteria (IC):** For a participant to be considered valid for this experiment, it was necessary to meet the following: Participants with a completed primary education (to ensure comprehension of the test's interactions and tasks); Participants who are already familiar with the DAL platform in a non-metaverse environment, so as to allow for a comparison with the metaverse; and participants with experience using web browsers and distance learning platforms, so that any resistance would be in relation to the technology being tested, rather than a lack of familiarity with the internet; **Exclusion Criteria (EC):** Even if a participant meets all the inclusion criteria, they will be ineligible to participate in the experiment if they: Have previously interacted with any DALverse functionality; Possess a certificate of completion for the course to be taken in the experiment; Have a motor impairment in their upper limbs (as the use of a mouse and keyboard is required for navigation within the environment); and have a visual impairment (as the NVDA screen reader does not function within the DALverse).

Having established the inclusion and exclusion criteria and identified the participants who met the required profile, the next stage consisted of operationalizing the Pilot Experiment. To ensure methodological clarity and reproducibility, the pilot test was conducted following a structured sequence of steps detailed below.

Step 1: Preparation: in this stage, before any data collection took place, participants were first presented with the Informed Consent Form (ICF). The form detailed the purpose of the study, the procedures involved, the voluntary nature of participation, and the use of interaction recordings for research analysis. Only after agreeing to the ICF did participants proceed to complete the initial questionnaire, which collected demographic information and basic profile data. All personal information and research records were handled confidentially in accordance with ethical guidelines;

Step 2: Presentation: before beginning the experiment, the participants were introduced to the activities they would be performing, the course that would be offered, and the virtual

platform where the course would be taught. An introduction to the metaverse environment was also provided, highlighting its immersive space for socialization, interaction, and collaboration;

Step 3: Briefing and Test Application: before each experimental session, participants received a quick orientation document ("DALverse/Metaverse Briefing")¹² that informed them about the test's objective and the step-by-step procedure. The material: (i) greeted the participant and explained that it was a test of the DALverse functionalities; (ii) indicated that communication would be maintained via Google Meet for initial support; (iii) requested the "Think Aloud" technique, asking the volunteers to verbalize their decisions during navigation; (iv) informed them that the exercise faithfully simulated a real distance learning course; and (v) provided temporary credentials (login and password) as well as the avatar movement keys – W (forward), S (backward), A (left), D (right) or the keyboard arrows. This briefing ensured that all participants began the task with the same level of operational understanding and without any doubts about the experiment's purpose. The participants performed activities from the Agile Methodology for Software Development course (topic 1 and topic 2) on the DAL platform. In addition to the proposed activities, such as exercises and evaluations, they were encouraged to use the DALverse to perform additional tasks. In the Pilot Experiment with non-disabled participants, communication took place primarily via voice and text chat, while the gestural avatars were used as a complementary channel—for instance, to signal turn-taking, agreement, or doubt—and to verify that the gesture repertoire operated correctly before being deployed with deaf participants and one hearing tutor, in the Main Experiment. During these activities, not only were the participants' performance observed, but also their interactions with the platform and the DALverse. The participants' engagement/motivation index and their perception of collaboration were also recorded during the activities.

Step 4: Results Collection: In addition to the results collected during the experiment, participants answered a questionnaire about their experience performing the course activities and the support provided by the DALverse. In it, participants' opinions were consulted about the influence of the DALverse on their learning, as well as suggestions for improvements and adjustments, both for future research protocols and for the functionalities of this immersive metaverse-based environment. This phase also included the application of the System Usability Scale (SUS) [Brooke, 2013];

Step 5: Results Analysis: in this phase, the data collected during the experiment were analyzed, in accordance with the proposed methodology, to verify the validity of collaborative interactions and the gestures of the animated avatars. Suggestions for potential improvements to the DALverse's functionalities were also considered.

In this study, the use of the metaverse was designed to meet the needs of distance learning classes for two topics within the Agile Software Development Methodology course. The pedagogical content addressed includes: the triangle of constraints and the waterfall model of software development.

¹²Briefing: <https://bit.ly/Briefing-JIS-2025>

The educational objective was to enable students to identify the contexts and applications of these structures and components. Interaction between students and teachers was facilitated through metaverse resources, which included avatar creation, communication via chat and voice, access to internet-connected computers, study materials, web-classes, and course-related videos. Furthermore, activities and exercises were available to the students.

Activities for students and tutors included a variety of interactions using metaverse resources that aligned with their objectives. These activities were designed to integrate DAL with the DALverse (the DAL metaverse), providing an immersive and interactive experience for participants. The main objectives were to present the metaverse and pedagogical content, evaluate student learning, and promote the collaborative construction of knowledge. Based on a set of tasks, the following scenario was developed:

- Task 0 – Introduction and definition of the metaverse: *“The metaverse is the combination of ‘meta’ (meaning beyond) and ‘verse’ from universe, indicating the next generation of the internet. Here, participants, represented by avatars, can interact with each other and with software applications in a three-dimensional virtual space. Metaverses are immersive three-dimensional virtual worlds where people interact with each other and with the environment, using the metaphor of the real world but without its physical limitations.”*
- Task 1 – Free navigation (all available resources as per participant’s choice): *“Before we begin the test tasks, I’d like you to explore the application freely. This will allow you to get to know the screen components, understand how they work, and familiarize yourself with the environment.”*
- Task 2 – Physically locate another participant in the metaverse and approach them (tested resources: environment entry, avatar, and avatar locomotion): *“Maria is a DELL collaborator who recently enrolled in a DAL course based on the metaverse. Upon accessing the system and participating in the class, she felt the need to look for another participant in the metaverse room. If you were in Maria’s place, how would you find another participant within the application?”*
- Task 3 – Communicate with another participant (tested resources: voice and text chat communication): *“João works at DELL and recently accessed a DAL course in the metaverse. He discovered that he can communicate with other participants in this environment and wants to clarify a question with the tutor. If you were in João’s place, how would you communicate with the other participants?”*
- Task 4 – Use the whiteboard to make a note. Note: if the whiteboard is in use, you can request permission and wait your turn (tested resource: virtual whiteboard): *“Júlia is a student in a DAL course in the metaverse. At a certain point, she realized the need to organize her ideas to share exercise solutions with colleagues and tutors, and decided to use the whiteboard to make a note. If you were in Júlia’s place, how would you use this resource?”*
- Task 5 – Screen sharing: *“Now that João has learned to*

communicate with other participants and use the whiteboard to take notes in the DAL metaverse environment, he would like to share his screen. If you were in João’s place, how would you use this resource?”

- Task 6 – Access the DAL Agile Methodology for Software Development course (tested resource: consuming class content): *“Lara, a DAL student, has learned to navigate the metaverse educational environment and has already used several resources. Now, she wants to attend the class and practice. To do this, she intends to access the Agile Methodology for Software Development course and study the content. If you were in Lara’s place, how would you access the class and the topic content?”*
- Task 7 – Collaborative activity between students on the class content (tested resource: collaboration between students using metaverse components): *“Pedro and Lara are students in the DAL Agile Methodology for Software Development course. The tutor has assigned an activity on the triangle of constraints (topic 1 of the course), and they must collaboratively draw the triangle (Figure 11 and Figure 12). If you were in Pedro’s or Lara’s place, how would you approach this activity in partnership with a colleague?”*

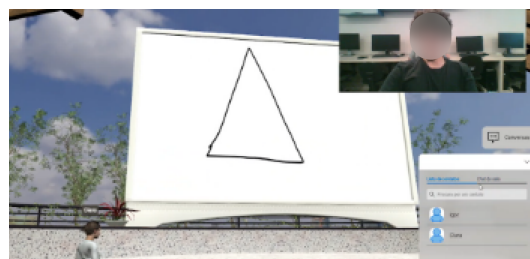


Figure 11. Hearing participant solving the triangle of constraints activity.

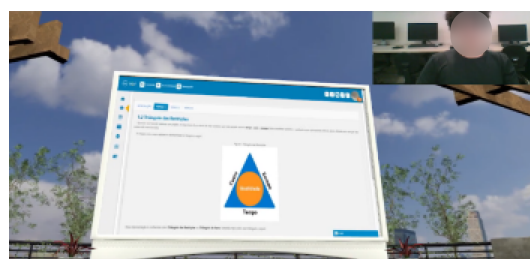


Figure 12. Hearing participant accessing and interacting with content on the DAL platform.

- Task 8 – Collaborative Challenge Proposed by the Tutor in the Metaverse (tested resource: collaboration between students and between students and tutors using metaverse components): *Helena is a tutor for the DAL Agile Methodology for Software Development course. To exercise the students’ learning, she proposes a challenge in the metaverse (Figure 13). Collaboratively, she begins the construction of the waterfall model of software development (topic 2 of the course), drawing the boxes corresponding to each phase of the process. The students Jorge and Raquel must, together, fill these boxes with the name of each stage of the process (Figure 14). Finally, they agree and choose one of them to share the screen, presenting the final solution they built (Figure 15). If*

you were in Jorge's or Raquel's place, how would you approach this challenge?"



Figure 13. Tutor presenting a challenge on the metaverse whiteboard.



Figure 14. Student solving the challenge assigned by the tutor.

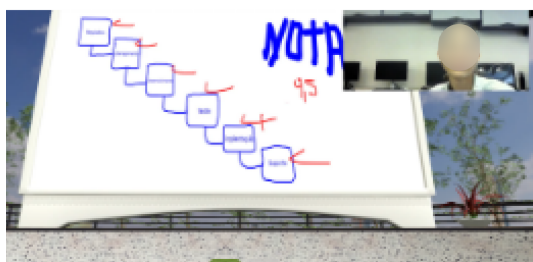


Figure 15. Tutor correcting a collaborative activity in the metaverse and presenting the correction to the class.

6.2 Main experiment

As in the Pilot Experiment, the protocol intentionally combined DAL for participant content consumption and DALverse for collaborative activities. Therefore, deaf participants first completed the learning module in DAL (with interpreter support when needed) and then performed the collaborative tasks inside DALverse. In these interactions, the tutor avatar represented the participation of the hearing participant.

The first phase of the Main Experiment consisted of **defining the study**, which analyzed the use of the metaverse as an inclusive learning environment in DE, focusing on students and alumni with disabilities. The experiment involved five deaf participants and one (hearing) tutor. Participants answered questionnaires on usability, learning perception, and motivation. The objective was to analyze the impact of animated gestures in avatars as a communication tool for the deaf in collaborative metaverse environments, to understand how these interactions promote collaboration and strengthen inclusion in educational activities.

On **study planning**, as to avoid redundancy, this section exclusively details the specific aspects concerning deaf participants, as the remainder of the study largely follows the same experimental design as Pilot Experiment.

For the definition and selection of participants, participants with hearing disabilities were recruited. Additionally, the same Inclusion Criteria (IC) and Exclusion Criteria (EC) used in Pilot Experiment were taken into consideration. Prior to the experiment, the same data on the participants' profiles were also collected, including, in this case, the collection of the disability profile.

As for the execution details, just as in Pilot Experiment, the same procedure was followed in Step 1 (Preparation), with the only addition to the Informed Consent Form (ICF) being that, in addition to usability, accessibility would also be verified in the test. In Step 2 (Presentation), the same procedure was followed, but with the assistance of a Libras interpreter. In Step 3 (Briefing and Test Application), before each experimental session, participants also received a quick orientation document ("Briefing DALverse/Metaverse"), with the difference from Pilot Experiment being that, at this point, there was help from the Libras interpreter. The participants performed the same activities from the Agile Methodology for Software Development course (topic 1 and topic 2) on the DAL platform as those performed in Pilot Experiment. In Step 4 (Results Collection), the same collection procedure from Pilot Experiment was followed. In Step 5 (Results Analysis), the same collection procedure from Pilot Experiment was followed. In the Main Experiment with deaf participants, communication combined text chat and predefined semantic gestures performed by the avatars. The Libras interpreter provided support during the presentation and briefing phases (for instance, clarifying instructions and answering questions), but not as the primary communication channel during the core collaborative tasks on the virtual whiteboard. The study did not require participants to rely exclusively on gestures; instead, it examined how these gestures could support and enrich text-based communication in collaborative activities.

7 Discussion and Analysis of Results

7.1 Overview

This section presents the data obtained from the experiments based on questionnaires, observations, and participant feedback. It discusses aspects such as usability, perceived inclusiveness, communicational effectiveness of the avatars, and limitations identified during the use of the platform.

New features were implemented to the DALverse, such as new avatars (customized and animated), enabling easy distinction between the teaching staff and students. This feature facilitates identification, interaction, and improves organization within the virtual environment. The choice is based on more formal clothing for tutors and more casual attire for students, as shown in the leftmost image in **Figure 16**.

DALverse offers avatar customization, allowing learners to change clothing, hair, and skin colors, as well as add accessibility accessories such as glasses and hearing aids. This promotes diversity and inclusion, valuing learners' identities. The platform also expands hair customization options, providing greater variety (see image on the right in **Figure 16**).

Learners can also interact with others through their avatars by performing gestures (see **Figure 17**).

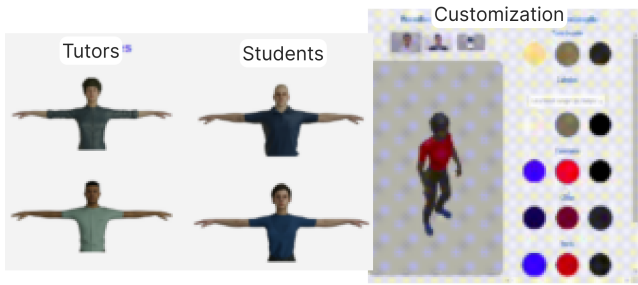


Figure 16. New avatars, accessories, and customization.



Figure 17. Animated gestures.

7.2 Pilot experiment

Before the beginning of the Pilot Experiment, a pre-experiment questionnaire was administered to collect baseline information about the participants. The purpose of this instrument was not to conduct a “pre-test” in the methodological sense, but rather to characterize the sample by gathering data on their profile, gender, age range, self-reported experience with web browsers and distance-learning environments, and whether they had any prior interaction with the DALverse environment.

The three participants were between 18 and 35 years old. Two out of three participants were in the 18–25 age range, and one out of three participants was between 26 and 35 years old. All three participants identified as female. Regarding experience with web browsers and e-learning platforms, one out of three participants reported beginner-level experience, one out of three reported intermediate experience, and one out of three reported advanced expertise. Additionally, all three participants stated that they had never interacted with the DALverse environment before this study.

On the **Figure 18** six screenshots are presented, they illustrate key moments of the collaborative activity conducted within the virtual environment. These images serve both as empirical evidence of the platform’s pedagogical potential and as documentation of the experimental protocol adopted.

- (a) **Gestural and verbal communication.** Is observed on **Figure 18 a)** shows two avatars performing gestures while engaging in voice dialogue, exemplifying the multimodal interaction supported by the platform. The combination of chat, audio, and body language helped reduce communication barriers and fostered social engagement among participants.
- (b) **Synchronous collaboration on the whiteboard.** In **Figure 18 b)**, participants are collaboratively constructing the project management triangle (Course Topic I). The avatars are positioned around the shared whiteboard, enabling simultaneous writing and real-time discussion—a

key feature for co-creation of visual artifacts.

- (c) **Sharing disciplinary content.** **Figure 18 c)** displays the waterfall model of software development (Course Topic II) projected on the whiteboard. This moment illustrates the ease with which instructors can present instructional materials without needing to switch to external tools.
- (d) **Student perspective.** **Figure 18 d)** shows a student’s point of view while interacting with the whiteboard. The first-person camera enhances the sense of presence within the 3D space, supporting focus and participant control over the learning process.
- (e) **Real-time tutor feedback.** **Figure 18 e)** illustrates students correcting a diagram in real time, accompanied by avatars representing the class. This continuous action–reaction flow embodies active learning principles and reflects the platform’s low latency.
- (f) **Panoramic view of the collaborative room.** Finally, **Figure 18 f)** synthesizes the spatial distribution of avatars, the fluidity of movement in the outdoor scene, and the coexistence of multiple media (gestures, voice, 3D objects). These elements combine to create an immersive, high-level collaborative environment aligned with contemporary demands of remote education.

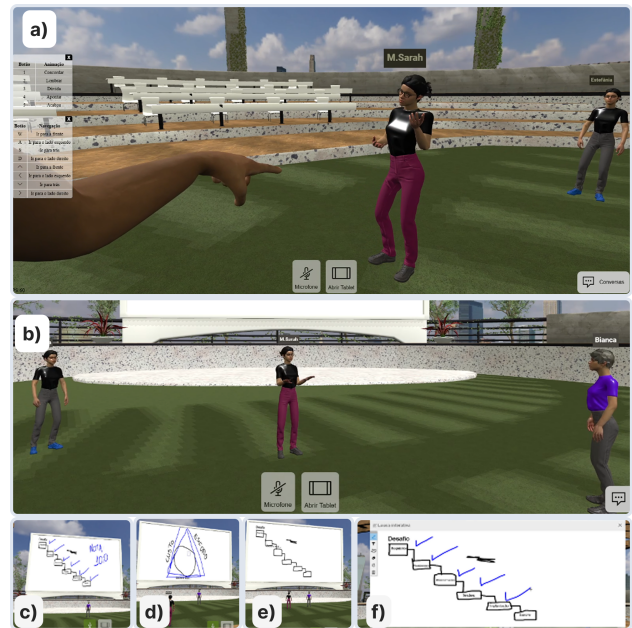


Figure 18. Learners performing collaborative activities (the written text on images is not relevant).

Taken together, the visual evidence supports three main findings: (i) **Multisensory Engagement:** gestures and locomotion enhance expressiveness, mitigating the “coldness” typically associated with traditional videoconferencing. (ii) **Support for Co-Creation:** the shared whiteboard allows abstract concepts to be externalized and collectively refined, fostering meaningful learning. It is important to note that this study does not provide a direct comparative evaluation between DALverse and traditional standalone collaborative whiteboard tools. Instead, participants’ reports indicate that the combination of a shared 3D environment, avatar co-presence, and gestural interaction afforded a different qualitative experience of joint attention and co-presence compared to conventional

2D tools. These perceived contributions relate primarily to embodied and spatial aspects of collaboration rather than to measurable performance gains. As such, the findings should be interpreted cautiously and serve as motivation for future controlled studies explicitly comparing metaverse-based environments with traditional collaborative platforms. **(iii) Continuous Feedback:** the possibility of immediate corrections and textual narration opens pathways for inclusive practices and adaptation to different student profiles. These observations are consistent with the idea that metaverse-based environments can enhance certain aspects of online courses—such as shared spatial context and multimodal interaction—although they also face significant limitations in adoption and scalability. This interpretation aligns with the findings of Radianti et al. [2020], whose systematic review shows that, despite the pedagogical potential of immersion and collaboration in virtual environments, VR/metaverse educational initiatives have not yet achieved widespread use due to recurring challenges in infrastructure, cost, usability, and technological maturity.

7.2.1 SUS evaluation

The average SUS score was 92.5, indicating excellent usability. This value reinforces the qualitative findings of high acceptance observed in interviews and focus groups. The consistency of responses suggests that, even with a small number of participants ($N = 3$), there is strong evidence of superior usability.

In the Pilot Experiment, we also applied an adapted version of the Constructivist On-line Learning Environment Survey (COLLES) questionnaire [Taylor and Maor, 2000] to obtain an exploratory indication of participants' perceived learning in the metaverse setting. The items covered dimensions such as relevance, reflection, interaction, peer support, and interpretation, rated on a seven-point Likert scale. Given the very small sample size ($N = 3$), these data were treated solely as subjective, self-reported perceptions rather than as evidence of measurable learning gains, and are therefore used only to contextualize participants' motivation and engagement with DALverse.

7.2.2 Qualitative evaluation of participant experience

In addition to the quantitative results obtained from the applied questionnaires, the qualitative analysis of students' experience reports reinforces the positive perceptions regarding the use of DALverse as a collaborative learning environment in DE. The testimonials highlighted that immersion and interaction in the metaverse contributed to participants' engagement and perceived learning.

Students emphasized that the experience in DALverse influenced their learning by providing new forms of interaction and collaboration. Examples include the following comments: (i) "I really liked it, especially the option to use the whiteboard and share the screen. It seems like we'll have new features such as opening files. It looks promising, and I would like to use it more often." [Student participant 1]; (ii) "It's a good immersive experience and helps with staying focused during the course." [Student participant 2]; and (iii) "Being an interactive environment, the exchange of ideas can be interesting." [Student participant 3].

In addition, the perception of the tools available on the platform was evaluated positively. Features such as gestures, microphone, and chat received favorable feedback and were considered essential for socialization and collaboration: (i) "In addition to the chat and microphone, I really enjoyed being able to move around and use gestures with the other students. Also, with screen sharing, it's easier to socialize and discuss, I'd say..." – [Student participant 1]; (ii) "For me, it was very good to use the communication features, such as the microphone and character actions, in addition to the immersive experience of actually being in a virtual environment with classmates." – [Student participant 2]; and (iii) "Immersive environment and advanced collaboration tools." – [Student participant 3].

Regarding points for improvement in DALverse to enhance socialization within DAL through immersion and collaboration: (i) "I think just improving the graphics a bit, adding actions like sitting, jumping... Other than that, I liked everything." – [Student participant 1]; (ii) "There could be more customization options for the avatars, so that changes would be saved and the character would keep the last used appearance. Also, some actions still need optimization, such as whiteboard latency and the fluidity and freedom of character movement." – [Student participant 2]; and (iii) "Text-to-speech for a more inclusive environment, and support for multiple platforms." – [Student participant 3].

Additionally, at the end of the session, participants were asked: "Regarding your interaction experience during this test, which collaborative environment do you prefer? The conventional DAL (without the metaverse) or DALverse (DAL with the metaverse environment)?" All participants indicated a preference for DALverse.

Given the very small sample size, these observations should be interpreted as qualitative insights into gesture usability and technical robustness, rather than as generalizable evidence about the broader population of hearing learners.

7.2.3 Conclusion of the pilot experiment

In this small-scale pilot, DALverse was perceived by the three hearing participants as a promising tool for immersive and collaborative learning, offering features that, in their view, foster focus, socialization, and idea exchange. Participants highlighted the immersive experience and interaction tools as key strengths, while also pointing to improvements such as enhanced graphics, smoother avatar movements, and increased accessibility. The unanimous preference for DALverse over the conventional DAL environment suggests its potential as an innovative educational setting, but these perceptions remain preliminary and cannot be generalized beyond this sample.

It is important to clarify that, in this phase, communication among participants occurred primarily through audio and text, meaning that the gestural animations did not play a central communicative role. Their function in the Pilot Experiment was limited to ecological validation (verifying whether gestures were technically functional and visually coherent within the environment) and baseline usability assessment (identifying clarity and timing issues before testing with deaf participants). Thus, we do not claim that gestures improved collaboration or task performance among hearing participants, as this was not their intended purpose at this

stage. The qualitative analysis supports the quantitative results, indicating the potential of the metaverse as an innovative resource for collaborative pedagogy. At the same time, the findings highlight the need to further improve and evaluate DALverse accessibility, particularly regarding how deaf participants collaborate in metaverse-based educational activities with both deaf and hearing peers. This participant profile was prioritized due to the linguistic and interactional complexity reported in the literature, as well as the research team's access to participants with hearing impairments.

7.3 Main experiment

It is important to note that the Main Experiment with deaf participants was not designed as a learning-gain study. Our primary focus in this phase was to investigate communicative experience, accessibility, and collaborative interaction in DALverse, rather than to quantify academic performance. In line with this goal, our analysis focuses on how deaf participants experienced the combination of text chat and gestural communication in DALverse, rather than on replacing all existing communication channels with avatar gestures alone. As a result, we did not administer pre- and post-tests or formal assessment instruments to compare learning outcomes across groups. The findings reported in this section therefore reflect participants' experience and perceived support for collaboration, not direct measures of knowledge acquisition.

Before the beginning of the main experiment, an initial profile questionnaire was administered to collect baseline sociodemographic, communication, and technology-use information about the participants. All five participants were deaf or hard-of-hearing participants associated with the DAL context. Most participants were between 36 and 45 years old while one participant was between 46 and 55 years old. The group included both male and female participants, with predominance of male participants. Most participants had completed secondary education, while one participant had completed undergraduate degree. Regarding technologic experience, participants reported heterogeneous levels of familiarity with web-based environments. Most participants indicated intermediate or advanced experience, while one participant reported beginner-level experience. Concerning communication aspects, all participants reported proficiency in Portuguese; however, oralization varied across the group with some participants being oralized and others not. This distinction is particularly relevant in the context of this study, it may influence interaction patterns, interpretation of visual cues, and communicative coordination within the metaverse environment.

The visual results of the immersive experience were cataloged below into 8 key moments.

- (a) **Access and Familiarization.** The first frame shows a deaf participant logging in and selecting their avatar demonstrating that the initial step is accessible without external support.
- (b) **Gesture Observation.** The second frame shows a deaf participant observing the gesture exchange between peers. This moment demonstrates that avatar body language is expressive enough to mediate understanding without audio support.

- (c) **Collaboration on Disciplinary Content.** In the third frame, the participant uses gestures to contribute to the construction of the constraints triangle (Topic I), confirming that co-creation tasks on the virtual whiteboard are feasible using visual signals.
- (d) **Peer Interaction.** The fourth frame highlights two deaf avatars communicating through predefined gestures, reinforcing the role of non-verbal communication as a central pedagogical resource.
- (e) **Free Exploration of the Environment.** The fifth frame presents a group of deaf participants exploring the 3D scenario, illustrating the fluidity of movement and freedom to experiment with body postures.
- (f) **"Do You Remember?" Gesture.** The sixth frame shows an avatar performing the memory-triggering gesture, indicating that specific signs can act as cues for recall and engagement.
- (g) **Indicating Continuation.** The seventh frame portrays an avatar gesturing for another to proceed with the activity, demonstrating sequential coordination and maintenance of collaborative flow.
- (h) **Requesting Confirmation.** Finally, the eighth frame illustrates the use of the confirmation gesture, validating the task performed and closing the feedback loop among peers.

The **Figure 19** brings together eight frames exemplifying the interaction between deaf participants in the DALverse environment, providing empirical evidence of the platform's inclusive potential.

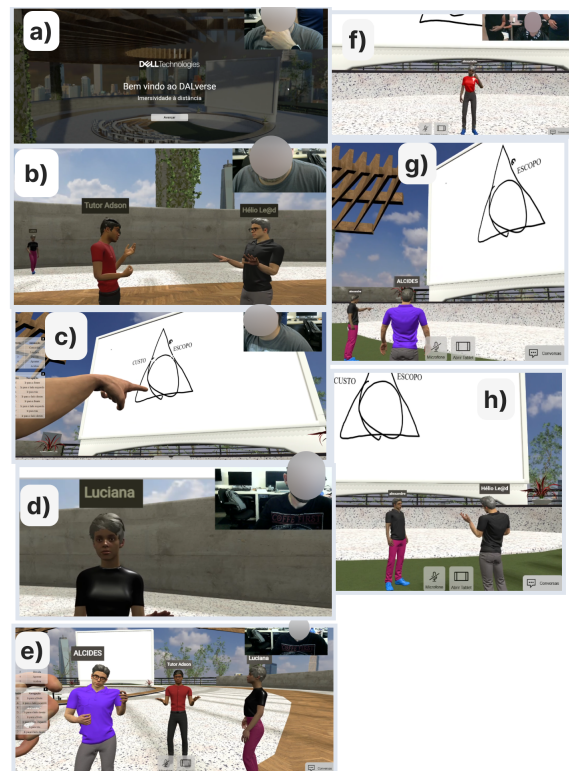


Figure 19. Collaborative Activities Mosaic.

These visual records support four main findings: (i) Navigation Autonomy: Deaf participants are able to access and explore DALverse without auditory support, thanks to its visual interface and integrated gestures; (ii) Communicative

Richness: The implemented signs cover essential pragmatic functions—recall, doubt, agreement, continuation, and closure—enabling rich conversations within an educational context; (iii) **Collaborative Engagement:** The combination of a shared whiteboard and gestural language enables the synchronous co-creation of conceptual content, fostering active learning; and (iv) **Real-Time Inclusion:** Gesture-based exchanges reduce the cognitive latency typically associated with captions or interpreters, facilitating immediate feedback and equitable participation.

In practice, this sense of autonomy was inferred from two converging sources: (i) observational data, showing that deaf participants accessed the platform, selected avatars, navigated the environment and manipulated the whiteboard without requesting interpreter assistance during the tasks; and (ii) self-reports in which they explicitly associated DALverse with greater independence in performing collaborative activities when compared to conventional DL tools.

Taken together, the evidence reinforces that DALverse meets the communicative needs of deaf learners and validates the use of predefined semantic gestures as an accessibility strategy within educational metaverse environments. It is recommended to expand the repertoire of signs in Libras (Brazilian Sign Language) and to optimize animation fluency to ensure naturalness and clarity.

7.3.1 SUS evaluation

The average SUS score was 62.0, classifying usability as moderate—acceptable, but with potential issues that may affect the user experience. The deviation from the score obtained in Pilot Experiment can be attributed, among other factors, to the absence of some additional gestures (30+) cataloged in the observational experiment but not yet implemented, which reduced expressiveness and, consequently, participants' perceived efficiency.

All five participants stated that they would like to use DALverse frequently, demonstrating a strong willingness to adopt the tool as part of their routine. Four out of five participants agreed that the system is easy to use, while the remaining participant expressed neutrality; there were no explicit disagreements, indicating minimal learning barriers. The same four participants recognized that the various functions are well integrated, indicating a coherent interface design free from noticeable friction. All five participants believed that new learners would learn to use the platform quickly and reported feeling confident when interacting with the environment, which suggests an intuitive onboarding flow and transparent feedback in this small group.

These results reveal five key strengths: voluntary adoption, a short learning curve, functional consistency, operational confidence, and harmonious integration of features. Together, these factors explain the SUS average of 62 points obtained in the experiment, placing DALverse in the "borderline acceptable" usability range.

7.3.2 Qualitative evaluation of participants' experience

In addition to the quantitative results obtained through the administered questionnaires, the qualitative analysis of students' experience reports provides a richer picture of how deaf par-

ticipants appropriated DALverse as a collaborative learning environment. Overall, the reports indicate a predominantly positive perception regarding the use of gestural avatars in the metaverse for peer-to-peer communication. First, several participants emphasized a sense of autonomy in navigation and task execution. They reported being able to log in, select avatars, move through the 3D space, and interact with the virtual whiteboard without relying on interpreters or hearing peers, which they associated with greater independence in the learning process. Second, participants highlighted the communicative value of the implemented gestures. They described the movements as clear and relatively natural, noting that the pragmatic repertoire (e.g., recall, doubt, agreement, continuation, closure) helped sustain the flow of collaboration on the whiteboard activities. Some reports explicitly mentioned that the gestures "felt close to Libras" in terms of structure and intention, which increased familiarity and comfort.

At the same time, the reports also underscored important limitations. Participants pointed out the absence of facial expressions, the need for a larger set of signs aligned with Libras, and occasional difficulties with movement and camera control. These issues were frequently linked to moments of misunderstanding or breakdowns in interaction, suggesting that the current implementation is still insufficient to fully replace the mediating role of interpreters. In this sense, the qualitative data reinforce that DALverse should be understood as a promising, but still partial, assistive resource in its present form. To avoid redundancy with the detailed narratives already made available as open data, we keep here¹³ a synthesized thematic analysis and refer interested readers to the full experience reports for further depth.

7.3.3 Conclusion of the main experiment

The experiment with five deaf participants and one tutor (hearing) suggests that animated gestures in avatars can support communication and inclusion in the metaverse under the conditions tested, and gestural avatars were preferred by all participants in this group. The gestures were generally evaluated positively; however, participants also requested greater facial expressiveness and signs more closely aligned with Brazilian Sign Language (Libras), as well as improvements in movement and navigation. Taken together, these findings highlight the potential of DALverse as an inclusive and collaborative learning tool for deaf participants, while reinforcing that they should be interpreted as preliminary and non-generalizable, given the small sample size and case-study design.

These obstacles translate into a concrete roadmap for improvement: (i) extending the gestural vocabulary in close collaboration with deaf learners and Libras interpreters; (ii) integrating facial animation and non-manual markers that are central to signed communication; and (iii) reworking locomotion and camera controls to reduce disorientation and support smoother transitions between participant exploration and shared whiteboard activities. Addressing these aspects is essential for DALverse to move from a promising prototype to a more mature, inclusive metaverse environment.

The moderate SUS score obtained in the Main Experiment is consistent with this limitation: several participants explicitly reported that the restricted repertoire of predefined

¹³Experience Reports: <https://bit.ly/Relatos-JIS-2025>

gestures, which only partially overlaps with Libras, made some interactions more effortful and constrained the expressiveness of their communication.

This limitation is also consistent with participants' qualitative reports, which indicate that the partial overlap between the predefined repertoire and Libras reduced communicative expressiveness in some moments. Therefore, we interpret the moderate usability scores as partially attributable to the current coverage constraints of the gestural set, rather than as a limitation of the metaverse approach itself.

8 Limitations and Threats

This study provides initial evidence that DALverse can support inclusive collaborative interactions. However, some methodological and contextual constraints warrant caution when generalizing the results, as detailed in **Table 1** on the next page.

Although DALverse has shown promising indicators, its exploratory nature, small sample size, and evolving prototype are limiting factors. Small samples are justified during the formative phase, particularly when supported by the literature. Future studies should involve larger samples, longitudinal evaluations, and multimodal metrics to validate the findings and enhance the inclusive potential of the educational metaverse.

9 Implications

This section discusses the implications of the findings, highlighting the potential of DALverse for inclusion in DE and outlining avenues for improvement. **Table 2** on the next page summarizes the main points, focusing on accessibility and usability.

10 Final Considerations

This study investigated how animated avatars can support more accessible collaborative interactions between deaf and hearing learners in an educational metaverse. Rather than demonstrating effectiveness in a statistical sense, our findings provide initial, small-scale evidence that deaf learners can perceive a metaverse environment with gestural avatars as a meaningful form of support for communication and collaboration in distance-learning contexts. Through an observational experiment, we identified 31 gestures relevant to direct communication, suggesting the potential of gestural avatars for mediating interactions. Participants expressed a clear preference for avatars with gestures and recognized similarities to Libras, although they also pointed out the lack of facial expressions and the limited gesture repertoire as significant constraints. These preliminary findings highlight the need for greater expressiveness, a broader set of avatars, the inclusion of other disabilities, and usability improvements such as simplified navigation and more accessible interaction controls. The study reinforces the importance of user-centered and interdisciplinary approaches in the development of assistive technologies for educational metaverses. It proposes, as next steps, deepening the qualitative analysis of participant narratives, expanding the gesture repertoire, and assessing the impact on collaborative learning and user experience in a more systematic manner.

Beyond the quantitative indicators, our findings also need to be interpreted in light of the linguistic diversity of deaf learners. Deaf communities are far from homogeneous: not all participants are equally fluent in written Portuguese, not all are oralized, and not all are familiar with formal glosa conventions. In this scenario, relying exclusively on textual communication may introduce additional barriers for some learners, even if, strictly speaking, the tasks could be completed via text alone. In DALverse, the predefined semantic gestures were therefore designed not as a replacement for text chat, but as an accessibility-oriented, non-verbal layer that approximates everyday visual and embodied communication practices. By providing cues for agreement, doubt, continuation, and closure, these gestures function as grounding signals that help regulate turn-taking, reduce ambiguity, and make collaborative interaction feel more natural for deaf participants.

It is also important to emphasize that, although some questionnaire items and experience reports refer to perceived learning, the present study was not designed to systematically measure learning gains (e.g., through pre- and post-tests or course grades). Our conclusions therefore focus on usability, communicative experience, and perceived support for collaboration, while the investigation of formal learning outcomes is left as an explicit goal for future work.

A key design implication emerging from the Main Experiment is that the current repertoire of gestures, while pragmatically useful, does not yet reach the expressiveness of Libras. This gap likely contributed to the moderate usability scores and to some of the communicative constraints reported by participants. In future work, we plan to expand this repertoire by co-designing and capturing gestures directly with Libras interpreters and deaf participants as in-world avatars, so that the semantic coverage and linguistic naturalness of the signs are systematically aligned with Libras.

From an accessibility standpoint, the experience reports point to concrete design directions for reducing interpreter dependence in future iterations of DALverse. Participants' suggestions converge on four priorities: (i) expanding the gesture repertoire to cover a broader range of Libras signs used in classroom discourse (e.g., topic transitions, content-specific terms); (ii) incorporating facial expressions and mouthings that are central to signed languages and are currently absent in the avatars; (iii) refining locomotion and camera controls to minimize disorientation and facilitate turn-taking around the whiteboard; and (iv) enabling deaf learners to configure shortcuts or macro-gestures for recurring expressions. Together, these actions are intended not to eliminate the role of interpreters, but to give deaf learners more direct control over communication in the metaverse, complementing mediated interaction with self-initiated gestural exchanges.

Beyond these findings, the present work advances theoretical, methodological, and applied dimensions by articulating a literature review on accessible metaverses and assistive technologies—conducted through a rapid review in a prior study—with a multistage empirical cycle for the design and evaluation of DALverse. The gestural avatar creation pipeline—based on Mixamo models and adapted to the communicative needs of Libras—proved technically feasible and suitable for extension to new gestures. The empirical strategy,

Table 1. Main validity threats of this study.

Domain	Limitation / Threat	Mitigation strategy / Next steps
Sample size	Both experiments involved only $N = 3$ hearing participants in Pilot Experiment and $N = 5$ deaf participants in Main Experiment. Small samples may inflate participant variation and limit statistical inference.	A small N was chosen due to the exploratory nature of the tests, aligned with Nielsen's guideline that five participants are sufficient to detect most issues. A previous study with $N = 30$ had already confirmed DALverse's motivational robustness, reducing the risk of novelty effect. Future stages will expand the sample and include control groups.
Sampling and representativeness	All participants, recruited by convenience, were affiliated with DAL. The age profile of the deaf participants (36–45 years) may not represent younger students.	The study will be replicated in other institutions and age groups, and will include participants with other disabilities to verify the transferability of the findings.
Internal validity	a) Instrumentation – the prototype did not include all 30+ cataloged gestures; b) Interpreter interference – in Main Experiment, the briefing mediated in Libras may have reduced perceived cognitive load.	Complete the implementation of the gestural repertoire, add facial expressions, and record usage logs to dissociate performance from interpreter support.
Construct validity	The SUS was administered using the original 5-point Likert scale [Brooke, 2013], adapted with Libras videos to ensure accessibility for deaf participants. Although necessary, this adaptation may influence how items are interpreted and may reduce measurement sensitivity compared to the 7-point variants occasionally reported in the literature, making direct comparisons with studies using expanded versions more difficult.	Interpret SUS scores cautiously and primarily in a descriptive manner. In future studies, employ triangulation with complementary instruments such as UMUX-LITE, or empirically evaluate the adapted SUS version to determine its equivalence and sensitivity for deaf participant populations.
External validity	The trials occurred in single sessions; learning and fatigue effects over a full course were not assessed.	Conduct longitudinal experiments tracking academic performance, retention, and spontaneous use of the metaverse.
Technological threats	Latency and graphical limitations of the virtual whiteboard may affect aesthetics and naturalness, according to participant reports.	Prioritize optimizations (rendering, network compression, and animation improvements) in future developments.
Researcher bias / desire to please	Some authors are affiliated with the lab responsible for the platform; participants may have felt inclined to provide positive feedback.	Anonymity and encouragement of criticism were ensured. External studies and blind analyses are planned to reinforce impartiality.

Table 2. Identified implications for improving the DALverse environment.

Aspect	Identified implication
Facial expression on avatars	Incorporate facial expressions to enrich emotional communication and increase the avatars' naturalness.
Gestures aligned with Libras	Adapt existing gestures to directly correspond to Libras signs, ensuring greater semantic accuracy.
Gestures similar to Libras	Preserve and improve gestures already similar to Libras, facilitating recognition by deaf learners.
Avatar diversity	Create avatars representing different types of disabilities, expanding inclusion and personalization in the environment.
Accessibility features	Provide accessories such as hearing aids and glasses to reinforce identity and visual accessibility.
"Leave room" button	Include a visible and accessible exit button to promote learner control and navigation autonomy.
Graphics improvement	Enhance the graphical quality of the scene and avatars' appearance, increasing immersion and visual realism.
Avatar sitting	Allow avatars to sit and automatically focus on the board during presentations.
Avatar jumping	Implement jump animations to expand body expressiveness and interaction dynamism.
Save avatar preferences	Maintain avatar customizations between sessions to ensure continuity and familiarity.
Whiteboard and movement optimization	Reduce latency in whiteboard interactions and make avatar movements more fluid and natural.
Text narration	Include synthesized voice for texts, promoting inclusion and multiplatform accessibility.

beginning with a broader sample ($N = 34$) to assess initial motivation and perceptions, followed by smaller groups ($N = 3$ and $N = 5$) focused on in-depth experiential analysis, aligns with Nielsen's rationale that a small number of users can uncover the majority of critical usability issues, supporting agile and resource-efficient iteration. At the same time, we acknowledge that the reduced sample sizes limit statistical generalization and that the current gesture repertoire covers only a fraction of Libras, which is reflected in moderate evaluations and reports of communication gaps. Future work will focus on four main directions: (i) conducting longitudinal studies with larger and more diverse groups of deaf participants; (ii) expanding the gesture repertoire through co-design sessions with Libras interpreters and deaf participants; (iii) incorporating facial expressions and more advanced avatar expressiveness mechanisms; and (iv) evaluating DALverse in real educational deployments over longer periods to investigate collaborative learning outcomes and sustained accessibility perceptions.

Declarations

Authors' Contributions

The authors' contributions to the manuscript were distributed according to the CRediT taxonomy as follows: Adson Roberto Pontes Damasceno was responsible for Conceptualization, Investigation, Data and Experiment Validation, and Original Draft Writing; Saymon Holanda contributed with Formal Analysis, Validation, Review and Editing, and Design; José Vinícius Vieira Lima worked on Visualization and Writing – Review and Editing; Eduardo Alves Lima Caldas developed the Software; and Francisco Carlos de Mattos Brito Oliveira provided Supervision.

Competing interests

The authors declare that they have no competing interests. The research protocol, including all data-handling and reporting procedures, was reviewed and approved by the institutional ethics committee, and all analyses were conducted independently by the academic research team.

Availability of data and materials

The datasets, software, and study materials generated and/or analyzed during the current study are listed in **Table 3**. This table summarizes all materials shared as part of this research in accordance with open science practices. All files have been anonymized and are publicly accessible through stable short links. The shared materials follow the anonymization procedures approved by the institutional ethics board and comply with responsible data-sharing guidelines in accessibility and human-computer interaction research.

Material	Access Link
Gesture dataset and documentation	https://bit.ly/Gestures-JIS-2025
Raw interaction and experimental data	https://tinyurl.com/DadosBrutosJIS2025
Qualitative reports (non-disabled participants)	https://tinyurl.com/RelatosNaoPcDJIS2025
Qualitative reports (deaf participants)	https://bit.ly/Relatos-PcD-JIS-2025
Experimental briefing and study protocol	https://bit.ly/Briefing-JIS-2025
Consolidated participant narratives	https://bit.ly/Relatos-JIS-2025
PDF version of experimental questionnaire	https://bit.ly/Pos--test-JIS-2025
PDF version of experimental questionnaire (Reponse)	https://tinyurl.com/Response-Pos-test-JIS-2025

Table 3. Summary of datasets and materials made available for open-science reproducibility.

Further relevant information

During the preparation of this article, generative artificial intelligence tools were used to support language revision, textual restructuring, organization of ideas, improvement of clarity in academic writing, conversion of tables into LaTeX format, and assistance with LaTeX commands required for manuscript formatting, such as those related to the insertion and organization of figures. The use of these tools was supervised by the authors, who reviewed, edited, and validated the generated or suggested content and assume full responsibility for the final version of the article.

References

- Alfaisal, R., Hashim, H., and Azizan, U. H. (2022). Meta-verse system adoption in education: a systematic literature review. *Journal of Computers in Education*, pages 1–45. DOI: <https://doi.org/10.1007/s40692-022-00256-6>.
- Ball, M. (2020). The metaverse: What it is, where to find it, and who will build it. <https://www.matthewball.co/all/themetaverse>. Accessed: 2026-07-02.
- Barbosa, S. D. J., Silva, B. S. d., Silveira, M. S., Gasparini, I., Darin, T., and Barbosa, G. D. J. (2021). *Human-Computer Interaction and User Experience*. Self-publishing.
- Beane, A. (2012). *3D Animation Essentials*. John Wiley & Sons.
- Bersch, R. (2008). Introduction to assistive technology. *Porto Alegre: CEDI*, 21.
- Brooke, J. (2013). Sus: A retrospective. *Journal of Usability Studies*.
- Caivano, D. S., Traverso, A., and Rodríguez, M. (2008). *El brief de diseño: teoría y práctica para la elaboración de estrategias de diseño gráfico*. Ediciones Infinito, Buenos Aires.

- Cartaxo, B., Pinto, G., and Soares, S. (2018). The role of rapid reviews in supporting decision-making in software engineering practice. In *Proceedings of the 22nd International Conference on Evaluation and Assessment in Software Engineering 2018*, pages 24–34. DOI: <https://doi.org/10.1145/3210459.3210462>.
- Daly, J. and Reitmayr, G. (2018). Avatar distinction in virtual environments: Identity, recognition, and interaction. *Journal of Virtual Reality and Broadcasting*, 15(1).
- Damasceno, A., Silva, L., Barros, E., and Oliveira, F. (2024a). Dalverse: Assistive technology for inclusion of people with disabilities in distance education through a metaverse-based environment. In *2024 IEEE International Conference on Advanced Learning Technologies (ICALT)*, pages 142–146. DOI: <https://doi.org/10.1109/ICALT61570.2024.00047>.
- Damasceno, A., Soares, P., Santos, I., Souza, J., and Oliveira, F. (2023). Assistive technology for distance education in metaverse-based environment: A rapid review. *Anais do XXXIV Simpósio Brasileiro de Informática na Educação*, pages 693–706. DOI: <https://doi.org/10.5753/sbie.2023.234543>.
- Damasceno, A. R., da Cunha, L. C. C., De Sampaio, J. V. F., Dantas, A. B., Barros, E. M., Maia, P. H. M., and Oliveira, F. C. (2022). A recommendation system framework for educational content reinforcement in virtual learning environments. In *CSEDU (1)*, pages 228–235. DOI: <https://doi.org/10.5220/0011032000003182>.
- Damasceno, A. R., Martins, A. R., Chagas, M. L., Barros, E. M., Maia, P. H. M., and Oliveira, F. C. (2020). Stuart: an intelligent tutoring system for increasing scalability of distance education courses. In *Proceedings of the 19th Brazilian Symposium on Human Factors in Computing Systems*, pages 1–10. DOI: <https://doi.org/10.1145/3424953.3426640>.
- Damasceno, A. R., Silva, L. C., Barros, E. M., and Oliveira, F. C. (2024b). Metaverse4deaf: Assistive technology for inclusion of people with hearing impairment in distance education through a metaverse-based environment. In *CSEDU (1)*, pages 510–517. DOI: <https://doi.org/10.5220/0012700200003693>.
- Damasceno, A. R. P., Lima, J. V. V., Caldas, E. A. L., Silva, L. C., and Oliveira, F. C. d. M. B. (2025). Understanding collaborative interaction and inclusion of people with disabilities in metaverse-based distance education environments: A quasi-experiment and its implications for dalverse. *Brazilian Journal of Computers in Education (RBIE)*. DOI: <https://doi.org/10.5753/rbie.2025.5140>.
- Davis, A., Murphy, J., Owens, D., Khazanchi, D., and Zigurs, I. (2009). Avatars, people, and virtual worlds: Foundations for research in metaverses. *Journal of the Association for Information Systems*, 10(2):1. DOI: <https://doi.org/10.17705/1jais.00183>.
- de Classe, T. M., de Castro, R. M., and de Oliveira, E. G. (2023). Metaverse as a learning environment for hybrid education. *RIED. Ibero-American Journal of Distance Education*, 26(2). DOI: <https://doi.org/10.5944/ried.26.2.36097>.
- de MB Oliveira, F. C., de Freitas, A. T., de Araujo, T. A., Silva, L. C., Queiroz, B. d. S., and Soares, É. F. (2016). It education strategies for the deaf-assuring employability. In *International Conference on Enterprise Information Systems*, volume 3, pages 473–482. SCITEPRESS.
- Fernandes, F. and Werner, C. (2022). Accessibility in the metaverse: Are we prepared? In *Proceedings of the 13th Workshop on Aspects of Human-Computer Interaction for the Social Web*, pages 9–15. SBC. DOI: <https://doi.org/10.5753/waihcws.2022.226618>.
- Jovanović, A. et al. (2022). Vortex metaverse platform for gamified collaborative learning. *Electronics*, 11(3):317. DOI: <https://doi.org/10.3390/electronics11030317>.
- Kendon, A. (2004). *Gesture: Visible action as utterance*. Cambridge University Press.
- Kye, B., Han, N., Kim, E., Park, Y., and Jo, S. (2021). Educational applications of metaverse: possibilities and limitations. *Journal of educational evaluation for health professions*, 18. DOI: <https://doi.org/10.3352/jeehp.2021.18.32>.
- Lin, H., Wan, S., Gan, W., Chen, J., and Chao, H.-C. (2022). Metaverse in education: Vision, opportunities, and challenges. In *2022 IEEE International Conference on Big Data (Big Data)*, pages 2857–2866. IEEE. DOI: <https://doi.org/10.1109/BigData55660.2022.10021004>.
- McNeill, D. (1992). Hand and mind: What gestures reveal about thought univ.
- Mori, M., MacDorman, K. F., and Kageki, N. (2012). The uncanny valley [from the field]. *IEEE Robotics & automation magazine*, 19(2):98–100. DOI: <https://doi.org/10.1109/MRA.2012.2192811>.
- Nascimento, M. D., Queiroz, B., Guimaraes, M., Silva, L. C., Soares, E., Oliveira, F., Ribeiro, D., and Ferreira, C. (2017). Accessible learning. In *Proceedings of the Workshops of the Brazilian Congress on Computers in Education*, volume 6, page 110. DOI: <https://doi.org/10.5753/cbie.wcbie.2017.110>.
- Nielsen, J. (1994). *Usability engineering*. Morgan Kaufmann.
- Onggirawan, C. A., Kho, J. M., Kartiwa, A. P., Gunawan, A. A., et al. (2023). Systematic literature review: The adaptation of distance learning process during the covid-19 pandemic using virtual educational spaces in metaverse. *Procedia Computer Science*, 216:274–283. DOI: <https://doi.org/10.1016/j.procs.2022.12.137>.
- Palomino, P., Araújo, A., Silva, A., Araújo, R., Dermeval, D., Porto, G. L., Simanke, S., Cordeiro, T., and Lisboa, R. (2025). Beyond detection: A framework for transforming accessibility evaluations into implementable fixes. *Journal on Interactive Systems*, 16(1):461–472. DOI: <https://doi.org/10.5753/jis.2025.5518>.
- Quek, F. and Oliveira, F. (2013). Enabling the blind to see gestures. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 20(1):1–32. DOI: <https://doi.org/10.1145/2442106.2442110>.
- Radianti, J., Majchrzak, T., Fromm, J., and Wohlgenannt, I. (2020). A systematic review of immersive virtual reality in education: State of the art and future research agenda. *Computers & Education*, 147:103778. DOI: <https://doi.org/10.1016/j.compedu.2019.103778>.
- Reeves, B. and Nass, C. (1996). The media equation: How people treat computers, television, and new media like real people. *Cambridge, UK*, 10(10):19–36.
- Rodrigues, C. S. C., Nazareth, V., Azevedo, R. O., Barbosa,

- P., and Werner, C. (2025). Unseen: Advancing digital accessibility with binaural audio technology in an immersive gaming prototype. *Journal on Interactive Systems*, 16(1):98–108. DOI: <https://doi.org/10.5753/jis.2025.4439>.
- Rogers, Y., Sharp, H., and Preece, J. (2013). *Interaction Design*. Bookman Editora.
- Sansar Inc. (2024). Sansar: Social vr experiences platform. <https://sansar.com>. Accessed: 2026-06-27.
- Taylor, P. and Maor, D. (2000). Assessing the efficacy of online teaching with the constructivist on-line learning environment survey. In *Flexible futures in tertiary teaching. Proceedings of the 9th Annual Teaching Learning Forum*, pages 2–4. Citeseer.
- Tlili, A., Huang, R., Shehata, B., Liu, D., Zhao, J., Metwally, A. H. S., Wang, H., Denden, M., Bozkurt, A., Lee, L.-H., et al. (2022). Is metaverse in education a blessing or a curse: a combined content and bibliometric analysis. *Smart Learning Environments*, 9(1):1–31. DOI: <https://doi.org/10.1186/s40561-022-00205-x>.
- Vianna, W. B. and Pinto, A. L. (2017). Disability, accessibility, and assistive technology in libraries: relevant bibliometric aspects. *Perspectives in Information Science*, 22:125–151. DOI: <https://doi.org/10.1590/1981-5344/2951>.
- Vieira, M. C., Corrêa, Y., Santarosa, L. M., and Biazus, M. (2014). Analysis of non-manual expressions in portuguese–libras translator avatars. In *In XIX International Conference on Informatics in Education – TISE*, volume 10.
- Vircadia Project (2024). Vircadia: An open-source social virtual world platform. <https://vircadia.com>. Accessed: 2026-06-27.
- Xavier, A. N. (2017). Expression of intensity in libras. *Intercâmbio*, 36.