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"Pathways to the Metaverse": Exploring the User Experience Mechanisms Driving Technology Acceptance in Virtual Lab Visits with an LLM-powered Avatar

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"Pathways to the Metaverse": Exploring the User Experience Mechanisms Driving Technology Acceptance in Virtual Lab Visits with an LLM-powered Avatar

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Abstract

Metaverse environments combined with large language models (LLMs) enable guided interaction through LLM-powered avatars that function as embodied conversational agents. In our study, we examined how scholars interact with an LLM-powered avatar modeled after a real professor during a virtual reality (VR) tour of a research lab. As little is known about how metaverse characteristics shape the user experience (UX) mechanisms that drive acceptance of such technologies, we conducted a 2 (avatar realism: abstract vs. hyperrealistic) × 2 (immersion: desktop vs. headset-based VR) within-subjects study (N= 30), where academic participants engaged in a virtual lab tour guided by the professor avatar. We conducted path analyses on three conceptual models and, based on the results, proposed the Virtual Lab Acceptance Model (VLAM), which features an experiential path (where perceived immersion increases empathy towards the avatar and task enjoyment) and a rational path (where perceived realism increases avatar credibility and task confidence). Flow states amplify these pathways by strengthening task experiences. Task enjoyment is the strongest predictor of behavioral intention. These findings inform HCI research on metaverse characteristics to drive technology acceptance through UX mechanisms, yielding design implications for developing LLM-powered avatars for virtual labs.

CCS Concepts

• **Human-centered computing → Empirical studies in HCI**; **User studies**; **Virtual reality**; **Natural language interfaces**; **Systems and tools for interaction design**.

Keywords

Avatar, Metaverse, Virtual Reality, Realism, Immersion, Technology Acceptance, LLM, Virtual Labs

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1 Introduction

> "*To be able to see a user's face, hear their voice, and sense their emotion when they're talking–is incomparable.*"
> —a quote captured in a research meeting

Advances in immersive technologies and large language models (LLMs) have enabled interactive virtual environments populated by LLM-powered avatars. With the rise of the metaverse[1] [84, 119, 120], these systems combine immersive 3D environments with intelligent, adaptive interaction, allowing users to engage with virtual entities in ways that increasingly resemble face-to-face communication. In metaverse research, an avatar can be seen as a visual embodiment through which individuals are expressed and perceived in immersive environments: a representation of "self" in digital form that others can perceive and interact with, through which people project their identity, preferences, and social cues [31, 89, 108]. While early avatars were primarily visual representations with limited interactivity, recent advances in LLMs have enabled avatars to engage in adaptive, natural language dialogue grounded in contextual knowledge, substantially extending their realism and interactivity [9, 75, 90]. In this study, we focus on such LLM-powered avatars as embodied conversational agents that combine visual embodiment with interactive intelligence [10]. This positions our work at the intersection of human-computer interaction (HCI) and artificial intelligence (AI), examining how users experience and accept these intelligent, embodied avatar in immersive environments.

Prior work on avatars in virtual reality (VR) and other forms of extended reality (XR) has examined avatar realism, presence, trustworthiness, and the uncanny valley effect [67, 111, 116, 137], while research on immersion has investigated how modalities (e.g., headset vs. desktop) influence user engagement and system usability [32, 49, 113]. Yet previous studies rarely connect to the design of avatars in functional contexts such as virtual lab environments, where the representational function of avatars may differ significantly compared to, for example, entertainment contexts. By "virtual lab" [95], we refer to the representation of a real research lab in a virtual environment accessible through devices such as VR headsets or laptop browsers (see Figure 2). In our case, the avatar we experimented with was the lab's professor in metaverse environments (see Figure 1).

Figure 1: Visual representations of the professor avatar used in the study. Left: reference photo of the real professor (not shown to participants). Middle: hyperrealistic avatar. Right: abstract avatar.

Figure 2: Overview of the four zones of the virtual lab, with the professor avatar acting as a lab guide: (a) lab introduction, smart logistics, and visual quality (hyperrealistic avatar), (b) collaborative robot (abstract avatar), (c) 3D printing and milling machine (hyperrealistic avatar), (d) electronic testing machines (abstract avatar).

Previous research has explored virtual tours for museums [1], but to the best of our knowledge, research has not specifically focused on virtual lab tours, although some HCI research has been done on simulating virtual labs in the pre-LLM era [11, 95]. Representing a lab and its professor in the metaverse offers scalable, accessible, and around-the-clock lab visits without the professor's direct involvement. Such virtual lab tours provide remote audiences, including prospective students, collaborators, or policymakers, with opportunities to experience research environments and interact with an avatar without being physically present, reducing both time and travel costs. However, design choices about the *avatar realism* and the *immersion* modality of the virtual environment remain critical. Avatar realism spans from stylized, cartoon-like characters to photo-realistic digital humans [58, 103], with higher levels of avatar realism generally improving user experience (UX) [52, 67, 70, 109], while overly realistic avatars risk uncanny valley effects or diminishing appeal [111]. A similar trade-off applies to immersion: while headset-based VR can increase the sense of presence [18, 118, 129], it may also introduce cybersickness and ergonomic strain [59, 61, 122]. Although prior work has examined these dimensions, the mechanism of how avatar realism and immersion shape technology acceptance through UX factors remains underexplored. Against this backdrop, we propose the following research question: **How do metaverse characteristics, specifically avatar realism and immersion modality, shape UX mechanisms that drive technology acceptance of the virtual lab tour with an LLM-powered avatar?**

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[1] In this study, we define "metaverse" in a broad sense to include both VR technologies and browser-based virtual environments, as interfaces for users to access digital environments.

To address this research question, we employed a 2 × 2 within-subjects study with 30 participants, varying *avatar realism* (hyper-realistic vs. abstract) and *immersion* modality (desktop vs. headset-based VR). Participants freely toured a virtual lab guided by an LLM-powered professor avatar, asking questions via voice interaction. After each condition, participants completed a think-aloud survey [87] capturing their perception of the avatar (e.g., empathy, credibility), task experience (e.g., motivation, enjoyment), flow (e.g., focus, absorption), ergonomic strain (e.g., physical discomfort, muscular strain), and technology acceptance (e.g., perceived usefulness, behavior intention).

Our contribution is twofold. First, we empirically test how metaverse characteristics influence acceptance of LLM-powered avatar through UX mechanisms, using path analysis to compare alternative theoretical models that culminate in an integrated model called **VLAM** (**V**irtual **L**ab **A**cceptance **M**odel). Second, we outline practical implications for designing metaverse avatars, focusing on educational and collaborative settings such as virtual labs. Our findings extend ongoing discussions of avatar realism and immersion toward the broader question of how LLM-driven avatars are received and accepted in virtual lab environments.

2 Background and Related Work

2.1 LLM-Powered Avatars in the Metaverse

Avatars have been studied in HCI and virtual environments as visually embodied representations through which users express identity, presence, and social cues in digital spaces [31, 89, 108]. Traditionally, avatars have been understood primarily as graphical embodiments controlled by human users, with interaction limited to navigation, gesture, or predefined actions. Research has shown that avatar appearance, visual fidelity, and stylistic features influence users' perceptions of social presence, credibility, and engagement [39, 88, 125]. With advances in immersive technologies and the emergence of the metaverse, avatars have increasingly become central as interaction elements in high-fidelity virtual environments rather than peripheral representations [13, 14]. The shift from static or minimally interactive representations to animated, expressive avatars marks a significant step toward richer social interaction and immersion [53]. Prior work has explored how visual realism, motion quality, and expressive features of avatars shape user experience, including perceived realism, trust, and social connection [54, 55, 105]. LLMs have enabled avatars to function as embodied conversational agents, capable of adaptive dialogue and context-sensitive responses [9, 75, 90]. These technical advances extend avatars beyond static or scripted interactions by adding conversational depth and interactivity, which can influence UX, for example, by strengthening perceptions of naturalness and social presence [6]. These novel interaction techniques aim to make avatars represent people more realistically and immersively, allowing users to interact with avatars in virtual environments of high fidelity [26, 102]. Such avatars can convey identity, expertise, and social intent in ways that go beyond traditional visual representation alone, through the combination of visual embodiment, voice, and generated realistic behaviors [81].

However, prior research has rarely evaluated how metaverse characteristics like avatar realism and immersion modality jointly shape acceptance towards LLM-powered avatars. Most studies focus on comparing outcome measures without investigating the underlying UX mechanisms that drive technology acceptance [42, 77, 125], which forms a notable research gap. Addressing this gap is critical for advancing HCI scholarship, as it links immersive and generative AI technologies with the design of credible and usable avatars for "serious" metaverse applications, such as virtual lab tours that are accessible irrespective of time and space constraints.

2.2 The Effect of Avatar Realism on Metaverse User Experience

Avatar realism, consisting of visual fidelity, behavioral animation, and expressive detail, has a major impact on how users perceive and interact with avatars. In metaverse environments, avatar realism shapes impressions of credibility, empathy, and social presence, which in turn influence task engagement and overall UX [12, 92, 131].

A consistent finding across studies is that realistic appearance and motion tend to increase users' perception of authenticity and credibility. When avatars display lifelike facial expressions, accurate lip synchronization, and natural body movement, users are more likely to perceive them as competent and believable communicators [39, 88, 92]. For example, realistic avatars have been shown to improve trust in training and educational simulations by conveying domain expertise and emotional nuance [9, 56]. Conversely, low-fidelity or poorly animated avatars can reduce perceived professionalism and diminish user engagement [38, 80, 88]. However, avatar realism is not inherently positive: exceeding a certain perceptual threshold can produce uncanny or unsettling impressions, leading to adverse effects, such as discomfort or reduced trust [82, 112].

Beyond appearance, behavioral and expressive realism of an avatar, including gestures, gaze, and voice tone, has been found to play an equally important role in shaping empathy and social connection. Users respond more favorably to avatars that exhibit responsive, human-like timing and expressive cues, which help sustain attention and interaction fluency [2, 79, 134, 135]. Behavioral congruence also contributes to smoother conversational flow and perceived co-presence in virtual encounters [85, 110]. In contrast, when visual and behavioral realism are mismatched, such as a photorealistic face paired with rigid movements, the resulting dissonance can reduce user engagement [106, 137].

The effects of avatar realism also extend to task experience and motivation. Studies in education and professional collaboration suggest that credible avatars can increase confidence in the presented content and motivation to explore the environment [42, 99]. In learning scenarios, avatars with realistic expressions and domain-relevant communication styles enhance comprehension and satisfaction [50, 100]. Conversely, mismatched avatar realism, such as overly stylized or exaggerated features, can hinder concentration and decrease task relevance [100]. Contextual fit is therefore essential for realizing the benefits of avatar realism. The same level of visual fidelity that works well in entertainment or gaming may not be suitable for professional or educational settings. Research shows that moderate, contextually appropriate avatar realism, consistent with the user's expectations and the task's purpose, optimizes both trust and comfort [62, 136].

Overall, prior research shows that avatar realism influences multiple facets of UX, from social perception and empathy to confidence and motivation. Yet, despite extensive work on avatar realism in social and entertainment contexts, less is known about how it functions in task-oriented environments such as virtual laboratories. In particular, how avatar realism interacts with other metaverse characteristics like immersion to shape the psychological and experiential factors leading to technology acceptance remains an open question.

2.3 The Effect of Immersion on Metaverse User Experience

Immersion refers to the degree to which a virtual environment envelopes a user's sensory and cognitive channels, producing a compelling sense of "being there". It depends on system properties such as field of view, tracking accuracy, frame rate, and interaction responsiveness [115]. In metaverse contexts, immersion has been shown to influence how users experience presence, embodiment, engagement, and physical comfort in a wide range of tasks [18, 70, 78].

Studies consistently show that higher immersion increases presence and embodiment, leading users to perceive themselves physically and socially located in the virtual space [101, 125]. This intensifies emotional and attentional engagement, often contributing to stronger task absorption, enjoyment, and focus [17, 93]. In educational and training scenarios, immersive environments have been linked to improved motivation and engagement, though not always to better learning outcomes [18, 78]. The novelty and sensory load of head-mounted displays can increase cognitive demands, occasionally distracting from primary task goals. Thus, while immersion deepens presence and engagement, it can simultaneously challenge users' ability to manage information efficiently.

In practical applications, immersion shapes the quality of task experience. Students in headset-based virtual seminars report higher levels of focus, participation, and curiosity than in desktop conditions [17]. However, the same studies identify usability barriers, such as cybersickness, difficulties with note-taking, navigating menus, and maintaining prolonged concentration [17]. These issues revealed that the benefits of immersion depend on interface design choices that support cognitive control and minimize friction.

At the same time, immersion introduces ergonomic and physiological considerations. Head-mounted displays may cause neck strain, eye fatigue, or discomfort during extended sessions [63, 91]. Although these effects rarely prevent task completion, they can influence long-term acceptance and willingness to adopt immersive technologies in professional settings. As virtual environments become more prevalent in education, remote collaboration, and training, addressing such ergonomic constraints is increasingly critical for sustaining user engagement and comfort.

Overall, prior research establishes immersion as a powerful driver of engagement, presence, and concentration, while also highlighting its cognitive and physical demands that may impact usability and acceptance. What remains less understood is how these perceptual and experiential outcomes translate into technology acceptance.

2.4 Mechanisms Linking Metaverse User Experience to Technology Acceptance

Technology acceptance in metaverse environments depends not only on technical quality, but also on the psychological processes through which users evaluate and internalize their experiences [41]. Decades of research on technology adoption, beginning with the Technology Acceptance Model (TAM) [24] and its later extensions such as TAM2 [123], Unified Theory of Acceptance and Use of Technology (UTAUT) [124], and hedonic-motivation models [76], has shown that two core appraisals, perceived usefulness and perceived enjoyment, are the most consistent predictors of behavioral intention to use interactive systems. In immersive environments, however, these constructs are shaped by a broader set of experiential factors, including presence, empathy, flow, and embodiment, which blur the boundary between cognitive evaluation and affective engagement.

Prior metaverse studies suggest that acceptance is driven by two pathways: a (1) rational pathway, where users evaluate the system's credibility, trustworthiness, and utility; and an (2) experiential pathway, where users' sense of enjoyment, empathy, and absorption dominate behavioral intention [3, 5, 93, 98]. While earlier VR and AR studies typically emphasized usability and performance benefits [78, 117], more recent work positions affective constructs, such as immersion, flow, and enjoyment, as equally important drivers of adoption [50, 101]. These findings align with contemporary perspectives in HCI that frame metaverse experience as a cognitive–affective integration process, in which users' perceptions of presence and social connection influence their acceptance of technology [42, 73, 130].

Within this backdrop, rational mechanisms emphasize structured evaluation: how users form beliefs about the system's credibility, trustworthiness, and functional value. In metaverse interfaces, avatar realism and consistency of information presentation strengthen these judgments [9, 99]. Conversely, experiential mechanisms reflect intuitive, emotion-driven responses that emerge from immersion, empathy, and flow, which increase motivation and engagement [4, 76, 101]. Flow, in particular, has been conceptualized as a mediating construct linking sensory engagement and emotional satisfaction with behavioral intention [20, 48].

Despite these advances in theory, empirical studies rarely model these mechanisms together. Most research examines either the rational dimension of acceptance (e.g., usefulness, trust, usability) [40, 69, 72, 77, 123] or the experiential dimension (e.g., immersion, enjoyment, presence) [4, 34, 45, 98] in isolation. This separation obscures how these processes interact dynamically in immersive environments where avatars combine social, cognitive, and affective cues. This integration challenge is particularly pronounced in virtual lab tours guided by expert avatars. Unlike leisure-oriented VR experiences such as museum or tourism tours, virtual lab tours are professional interactions in which users assess the credibility, competence, and trustworthiness of both the environment and the guiding avatar, often in support of learning, collaboration, or career-related decisions [78, 98]. In such contexts, the avatar functions not only as a narrative guide but also as a proxy for real academic authority, making social judgments such as credibility and trust central to acceptance [88, 127]. As a result, experiential mechanisms (e.g., immersion, empathy, flow) and rational evaluations (e.g., credibility, usefulness, confidence) become tightly coupled, akin to cognitive–affective integration processes observed in prior work on immersive and hedonic systems [4, 45, 76]. While general technology acceptance models such as TAM or UTAUT capture important outcome-level predictors of adoption, they do not explicitly model these intertwined experiential–rational pathways in expert-guided, task-focused metaverse settings. To address this gap, the present study proposes an integrative modeling approach, tested through three conceptual models and an overall synthesis in an integrated model (see Section 3.4).

3 Method

3.1 Technical Setup

The study was implemented as a virtual lab tour application, available in two configurations: a headset-based VR version and a desktop-based VR version (see Figure 3). In both setups, participants interacted with a professor avatar of either a hyperrealistic version with a photorealistic appearance or an abstract version with animated visuals.

Hardware. For the headset condition, we used a Meta Quest 2 headset [2] wirelessly connected to a Windows desktop PC via the Meta Quest Link app. The participants explored the environment and triggered speech through the Meta Quest controllers. In the desktop condition, the application ran on a GPU-enabled laptop, with navigation handled through keyboard and trackpad input.

Figure 3: Experimental setup showing the two immersion modalities: headset-based VR with Meta Quest 2 (left) and desktop-based VR with laptop display (middle). The picture on the right shows moderator and participant positioning.

Software. The virtual lab was developed in Unity[3] game engine, modeled after an existing engineering research lab and segmented into four zones [94]. As shown in Figure 2, each zone represented a distinct functional area of the lab: (a) lab introduction and smart logistics, (b) collaborative robot, (c) 3D printing and milling, (d) electronic testing. The avatar was instantiated in two variants (see Figure 1): the hyperrealistic version was generated in Reallusion Character Creator[4] from photographic inputs, and the abstract version was produced in Ready Player Me[5]. Both versions were animated with lip-synchronized speech and employed a cloned professor voice created in ElevenLabs[6]. Conversational capability via natural language was enabled by the ConvAI[7] LLM suite, which provided a retrieval-augmented generation (RAG) pipeline for grounding responses in curated lab knowledge. The backend followed speech-to-text recognition, LLM response generation, and text-to-speech synthesis. Subtitles were displayed for accessibility.

User interaction. Participants could freely navigate within each zone using locomotion controls (controller-based teleportation in headset VR; keyboard-based movement in desktop VR) and initiate spoken interaction with the avatar at any time. No task-specific object manipulation was required; interaction focused on spatial exploration and conversational exchange with the avatar. Across all zones, the professor avatar acted as a guide, typically presenting high-level explanations of the lab's activities and facilities in response to participant questions.

Avatar validation. The representational quality of the created avatars was assessed by the professor on whom the avatars were modeled. The professor interacted with both the hyperrealistic and abstract avatars, rating their responses, appearance, tone, and suitability for representing him for the virtual lab tour application. Overall, he found both avatars satisfactory, describing the hyperrealistic version as "impressive", while considering the abstract version to be of lower quality. The professor confirmed that the avatars' responses reflected how he would typically answer in real interaction, and noted that the hyperrealistic version most closely matched his own appearance and manner of speaking. He also stated that he would feel comfortable being represented by the hyperrealistic avatar in the context of a virtual lab tour, but less so by the abstract one.

3.2 Participants

A power analysis conducted with `G*Power` [36] determined that at least 28 participants would be required to achieve 80% power for detecting medium effects ($f = 0.25$, $\alpha = .05$). To ensure sufficient statistical power, we recruited 30 participants through professional networks, with participation on a voluntary basis and not monetarily compensated. The eligibility criteria required fluency in English and active involvement in university-level research, ensuring that all participants could communicate with the avatar and meaningfully engage with the lab tour scenario and task.

Participants were between 22 and 44 years of age (M = 28.8, SD = 5.6, Median = 27.0), consisting of 63.3% (n = 19) who identified themselves as men and 36.7% (n = 11) as women. Most participants (83.3%, n = 25) had STEM backgrounds, while 16.7% (n = 5) came from non-STEM disciplines. This distribution reflects both the demographics of engineering research environments and the relevance of STEM expertise to the engineering lab tour scenario, while still incorporating diverse perspectives. Participants held varied professional roles, including doctoral researchers (53.3%, n =

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[2] Meta Quest 2: https://www.meta.com/fi/en/quest/products/quest-2/ [accessed: 20 Aug 2025]

[3] Unity: https://unity.com/ [accessed: 20 Aug 2025]

[4] Reallusion Character Creator: https://www.reallusion.com/character-creator/ [accessed: 20 August 2025]

[5] Ready Player Me: https://readyplayer.me/ [accessed: 20 August 2025]

[6] ElevenLabs: https://elevenlabs.io/ [accessed: 20 August 2025]

[7] ConvAI: https://convai.com/ [accessed: 20 August 2025]

16), research assistants (40.0%, n = 12), and faculty or staff (6.7%, n = 2). None of the participants were familiar with the specific lab and the professor featured in this study, although all were accustomed to research settings. This made the remote lab tour realistic and relevant, since the physical lab is abroad from the study site. Self-reported experience with avatars (M = 2.9, SD = 2.0) and VR (M = 3.2, SD = 1.8) varied considerably on a 7-point scale, suggesting a heterogeneous sample in terms of prior exposure. The group was also internationally diverse, representing 14 nationalities.

The study adhered to our institutional ethical guidelines. The university's research ethics committee ruled that formal approval was not required, as no sensitive or high-risk data was involved. In accordance with institutional protocols, participants received an information sheet and privacy notice. An informed consent was obtained before participation. Participants were encouraged to raise questions at any point during the study. All data were anonymized using participant IDs, securely stored on university servers, and handled in accordance with institutional data management and retention policies. Access to the data was restricted to the research team.

3.3 Study Design, Scenario, and Task

We employed a 2 × 2 within-subject design with two independent variables: (1) avatar realism: *hyperrealistic* vs. *abstract.* (2) immersion modality: *headset* vs. *desktop* VR. This resulted in four experimental conditions: Hyperrealistic & Headset, Abstract & Headset, Hyperrealistic & Desktop, and Abstract & Desktop. The condition order was counterbalanced using a Latin Square [60], distributed as evenly as possible across the participants, with small deviations due to the final sample size (N = 30). Each participant explored four different lab scenes. The scene order was fixed to preserve the narrative coherence of the lab tour, while the order of conditions was randomized within each scene based on the assigned Latin square sequence.

The study scenario situated participants in a virtual engineering lab guided by an LLM-powered avatar modeled after the professor of that lab. The scenario was designed to illustrate emerging applications of metaverse and LLM technologies for training, onboarding, and stakeholder engagement. Creating a digital replica of the lab and its leading professor extended the environment beyond physical constraints and enabled accessible lab visits for diverse stakeholder groups, including (1) prospective students evaluating whether to join the lab, (2) industry collaborators assessing the lab's competencies and potential partnerships, and (3) policymakers and funders evaluating the lab's research alignments with broader goals. In the study, participants were instructed to take on the role of prospective researchers considering joining the lab. Their task was to freely explore the virtual lab environment and interact with the avatar to gather relevant information about the lab's research facilities, activities, operations, and members.

Each session lasted approximately 85 minutes and followed a structured protocol (see Appendix A). Upon arrival, participants were welcomed, provided with an information sheet, privacy notice, and consent form, and given time to review and sign them. After obtaining consent, participants completed a background survey that captured their demographics, prior VR and avatar experience, and familiarity with the target lab. They then received a briefing on the task and technical instructions, including how to navigate the virtual lab environment, operate the voice interface, and interact with the professor avatar.

As per the within-subjects design, each participant completed all four experimental conditions. In each condition, participants spent five minutes exploring a different part of the lab, during which they could freely move around in the virtual environment and engage in spoken dialogue with the avatar, typically asking multiple open-ended questions about research projects and facilities, and receiving conversational responses. After each condition, participants completed a post-condition survey (see Appendix B) assessing their perceptions of the avatar, task experience, flow status, ergonomic strain, and technology acceptance. During survey completion, participants were encouraged to think aloud, verbalizing their reasoning and impressions. (Think-aloud was not applied during active system use, as it would have interfered with interaction with the avatar.) After completing all four conditions, participants joined a semi-structured interview. Both the think-aloud responses and interviews were audio-recorded and transcribed, providing qualitative context and triangulation to complement the survey data. We used these materials to support interpretation of the path-model findings, without conducting a separate qualitative-only analysis.

3.4 Conceptual Models and Their Reasoning

In accordance with our research question and the literature review performed in Section 2, we measured the participants' experiences with the post-condition survey (see Appendix B). All quantitative items used 7-point Likert scales. Where available, measurement items were adapted from established and validated scales reported in prior literature [7, 8, 23, 25, 33, 42, 63, 86, 104, 127], but implemented in concise, context-adapted measures, tailored to the virtual lab tour context, as opposed to deploying full standardized questionnaires. While individual variables were measured as single items, each conceptual construct in our models was operationalized through multiple theoretically grounded variables. Although avatar visual realism and immersion modality were manipulated experimentally as part of the 2×2 study design, the conceptual models use participants' *perceived* realism and *perceived* immersion as explanatory variables. This modeling choice reflects the focus of VLAM on how users' subjective interpretations of visual embodiment and immersion, rather than condition assignment alone, drive downstream experiential and rational acceptance mechanisms. In line with the focus of our analysis, Table 1 reports only the measures that were included in our conceptual models and subsequent data analysis.

Based on conceptual deliberation of our research question in relation to the study variables, one of the senior researchers involved in this project developed five "candidate models" that could explain users' acceptance of virtual research labs. The study and candidate models were not preregistered. Instead, the models were theory-driven and specified through an author deliberation process grounded in prior literature on technology acceptance, flow, and avatar-mediated interaction. The idea was to progress through candidate models toward a more comprehensive, "integrated" model (which then evolved into the VLAM). The exercise was inspired

Table 1: Study variables. Measurement items available in Appendix B.

Construct	Variables	Key references
Metaverse characteristics	Perceived immersion; Perceived realism	[42]
Avatar perceptions	Empathy; Sense of presence; Credibility; Trustworthiness; Behavior naturalness	[7, 8, 104, 127]
Task experience	Confidence; Motivation; Enjoyment	[23]
Flow	Focus; Absorption; Time distortion	[33]
Technology Acceptance	Perceived usefulness; Adoption intention	[25]
Ergonomic strain	Physical discomfort; Muscular strain	[63, 86]

by the notion that "all models are wrong, but many are useful." [37]. These candidate models were presented to other authors and reviewed; later, two were removed because one was overly complex and the other lacked logical merit relative to the remaining models. Therefore, three models were kept for testing and reporting, as this number was deemed to provide an interesting "multi-lens" perspective to UX drivers of the technology acceptance, similar to previous work at the intersection of HCI and AI [133]. Table 2 shows each model and its logic is further elaborated in the following. Overall, research in technology acceptance often reports a single model without articulating the specific experiments and steps taken to arrive at that model. However, by developing multiple simpler models that converge toward a unified model, our approach makes it more transparent how different facets of the simpler models contribute to the larger VLAM model.

Model 1: Technology acceptance through avatar perception. M1 posits that metaverse characteristics (perceived immersion and perceived realism) primarily influence technology acceptance through social connection with avatars. Immersion and realism influence users' perception of the empathy, credibility, trustworthiness, or behavioral naturalness of the avatar. These impressions then shape users' confidence, enjoyment, and motivation in task experiences, which ultimately drive the acceptance of virtual lab technology, including perceived usefulness and behavioral intention, which are two relevant constructs identified in previous literature [68]. The model positions social connection with the avatar as a key driver to technology acceptance [57].

Model 2: Dual-path processing. M2 is based on the premise that users process metaverse technology through two distinct psychological pathways. First, the *experiential path* (analogous to affective processing) begins with perceived immersion, which adds to the sense of presence (avatar perception) and enjoyment (task experience). These, in turn, support deeper absorption and focus (flow), which ultimately contributes to behavioral intention to accept the virtual lab technology; a mechanism similar to the one observed in previous work [20, 48]. Second, we surmise that the *rational path* (analogous to cognitive evaluation) begins with realism, which improves credibility and trustworthiness (avatar perception). These judgments increase perceived usefulness (technology acceptance), which in turn supports the behavioral intention to accept the technology. Ergonomic strain can disrupt either pathway, but may differentially impact cognitive versus affective processing [97, 128].

Model 3: Flow-mediated task experience. M3 suggests that flow states are the critical psychological mechanism linking metaverse characteristics to positive technology acceptance, which aligns with previous work in a different context [101]. Immersion and realism create the focused and absorbed mental state characteristic of flow, which then supports task confidence, motivation, and enjoyment. Meanwhile, empathy towards avatars provides an alternative social route to a positive task experience that operates independently of the flow state. In both cases, improved task experience leads to higher technology acceptance, including perceived usefulness and behavioral intention [50, 107].

3.5 Data Analysis

Our analysis began with data preparation, followed by path analysis to test three conceptual models, and progressed toward an integrated model that synthesized their core pathways. Qualitative materials (open-ended survey responses, think-aloud protocols, and interviews) were used opportunistically to contextualize and triangulate the main quantitative findings, with selected quotes included in the results. The procedures taken are explained as follows.

Survey responses were exported from Qualtrics, cleaned, and reformatted into long-format tables. Duplicate headers and metadata fields were removed, and scale items were numerically coded from 1 to 7. Participant identifiers were standardized, and predictors used in path equations (perceived immersion, perceived realism) were mean-centered to scale homogeneously. We tested the three path models (Models 1-3; see Table 2) using sequential ordinary least squares (OLS) regressions with clustered standard errors by participant to account for the within-subjects design. In this approach, each hypothesized path is estimated as a separate regression equation in the causal order specified by the model. This sequential estimation allows us to test indirect and mediated relationships step by step, while maintaining transparency and interpretability of individual effects. Path analysis was applied instead of structural equation modeling (SEM) [121] because of its suitability to our study. SEM generally requires a larger sample size (200+ items) with multiple question measurements. While our study employed an observational sample ($N = 120$, derived from 30 participants × 4 conditions) and single-item measures, making path analysis a suitable choice, especially in a repeated measures design (where each person does multiple conditions). To aid interpretation, we categorized standardized path coefficients by magnitude following common guidelines in behavioral research [22]: $|\beta| \geq 0.5$ as large, $0.3 \leq |\beta| < 0.5$ as medium, and $|\beta| < 0.3$ as small effects.

Our analysis proceeded from simpler models that tested specific aspects of users' virtual lab tour experience toward a fuller synthesis. After evaluating the three candidate models separately, we developed an integrated model that amalgamates their core elements: a

Table 2: Theoretical models linking metaverse characteristics and technology acceptance.

Model	Description
Model 1	**Technology Acceptance through Avatar Perception** *Core pathway:* Perceived Immersion/Realism → Avatar Perception → Task Experience → Technology Acceptance *Key mediators:* Empathy, credibility, trustworthiness, behavior naturalness (avatar perception); confidence, enjoyment, motivation (task experience)
Model 2	**Dual-Path Processing Model** *Experiential path:* Perceived Immersion → Presence/Enjoyment → Flow → Behavioral Intention *Rational path:* Perceived Realism → Credibility/Trustworthiness → Perceived Usefulness *Inhibiting factors:* Physical discomfort, muscular strain (ergonomic strain)
Model 3	**Flow-Mediated Task Experience Model** *Primary pathway:* Perceived Immersion/Realism → Flow → Task Experience → Technology Acceptance *Flow components:* Focus, absorption, time distortion *Parallel mediator:* Empathy (avatar perception) contributes directly to task experience

cognitive pathway (perceived realism → credibility/trustworthiness), an affective pathway (perceived immersion → empathy/naturalness), and flow-based amplifiers linking metaverse characteristics to task experience. Like the candidate models, the integrated model was assessed using path analysis with sequential regression modeling.

4 Results

4.1 Model 1: Technology Acceptance through Avatar Perception

Model 1 (see Figure 4) examined whether perceived realism shapes technology acceptance primarily through perceptions of the avatar and subsequent task experiences. The model demonstrated moderate overall fit with an average $R^2 = 0.349$ across all equations, with individual equation performance ranging from weak (trustworthiness: $R^2 = 0.081$, $F(2, 117) = 5.178$, $p = 0.007$) to strong (usefulness: $R^2 = 0.559$, $F(3, 116) = 49.042$, $p < 0.001$).

Metaverse Characteristics → Avatar Perception. Perceived realism was the dominant predictor of avatar perception. It strongly predicted behavioral naturalness ($\beta = 0.557$, $p < 0.001$), credibility ($\beta = 0.367$, $p < 0.001$), trustworthiness ($\beta = 0.309$, $p = 0.006$), and empathy ($\beta = 0.279$, $p = 0.009$). Participants confirmed this view, for example, noting that "*the professor avatar looked and sounded quite convincing, I could easily believe it was a real person talking to me*" (P7), and that "*in the realistic version, I felt he was more credible, like I could trust the information more*" (P12). In contrast, perceived immersion showed only weak or marginal associations with these variables and did not significantly contribute to most avatar perceptions. This suggests that perceived realism, more than perceived immersion, influences how users assess the virtual professor avatar.

Avatar Perception → Task Experience. Among the avatar perception variables, empathy was the most influential mediator of task experience, significantly predicting confidence ($\beta = 0.370$, $p < 0.001$), enjoyment ($\beta = 0.432$, $p < 0.001$), and motivation ($\beta = 0.319$, $p < 0.001$). Credibility contributed smaller effects on confidence ($\beta = 0.215$, $p = 0.034$) and motivation ($\beta = 0.298$, $p = 0.002$), while behavioral naturalness predicted confidence ($\beta = 0.206$, $p = 0.015$) and enjoyment ($\beta = 0.161$, $p = 0.041$). In contrast, trustworthiness showed no significant influence on task-related outcomes. These findings suggest that affective connection (i.e., empathy) is a stronger driver of task experience than purely cognitive perceptions such as credibility or trustworthiness. Participants described these effects directly, for example: "*When he spoke in a way that felt empathetic, I enjoyed the task more and felt motivated to keep asking questions*" (P15), and "*It was easier to feel engaged when the virtual professor seemed to care or understand, not just when it looked real*" (P23). Credibility gave users confidence: "*I felt more confident in the lab information because the avatar seemed knowledgeable and credible*" (P04). Similarly, behavioral naturalness supported enjoyment: "*His movements were natural enough that it made the interaction smoother and more fun*" (P11).

Task Experience → Technology Acceptance. Task enjoyment was the strongest predictor of downstream acceptance outcomes, exerting a large effect on behavioral intention ($\beta = 0.609$, $p < 0.001$) and a medium effect on perceived usefulness ($\beta = 0.417$, $p < 0.001$). Confidence also contributed significantly to perceived usefulness ($\beta = 0.381$, $p < 0.001$), while motivation showed no direct effect on either usefulness or intention. This was reflected in participants' comments, for example: "*I would actually use this kind of virtual lab if it was always this enjoyable and easy to explore*" (P17), and "*Because I felt confident in what I learned, I could see how this would be a useful tool for students*" (P28).

In summary, Model 1 reveals a layered pathway in which perceived realism shapes avatar perceptions, empathy amplifies task experiences, and enjoyment is a critical mechanism linking task experience to technology acceptance. This suggests that virtual lab acceptance requires, in addition to technical quality, avatars that elicit empathy and enjoyment in users.

4.2 Model 2: Dual-Path Processing Model

Model 2 (see Figure 5) investigated users' acceptance of virtual lab technology in relation to two parallel mechanisms: an experiential path driven by perceived immersion and affective responses, and a rational path driven by perceived realism and cognitive evaluation. A third set of predictors tested the hypothesized inhibitory role

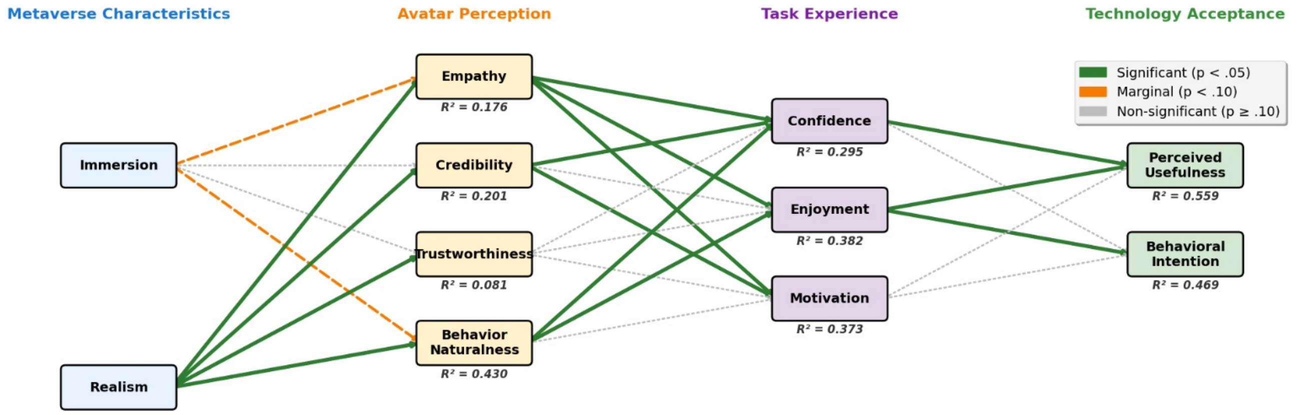

Figure 4: Results from Model 1: Technology Acceptance through Avatar Perception. Perceived realism strongly predicts avatar perception variables, especially behavioral naturalness and credibility. Empathy is the primary mediator of task experience, while credibility and behavioral naturalness exert smaller but distinct effects on confidence, motivation, and enjoyment. Task enjoyment is the strongest predictor of technology acceptance, driving both perceived usefulness and behavioral intention.

of ergonomic strain. The model achieved moderate overall performance with an average $R^2 = 0.311$, with particularly strong fits for sense of presence ($R^2 = 0.491$, $F(1, 118) = 113.963$, $p < 0.001$) and behavioral intention ($R^2 = 0.425$, $F(5, 114) = 16.861$, $p < 0.001$).

Experiential Path. Perceived immersion strongly predicted sense of presence ($\beta = 0.701$, $p < 0.001$) and task enjoyment ($\beta = 0.549$, $p < 0.001$). Of these, enjoyment subsequently predicted flow states: enjoyment predicted absorption ($\beta = 0.502$, $p < 0.001$) and focus ($\beta = 0.472$, $p < 0.001$), while sense of presence showed no downstream effects. In turn, absorption was a significant predictor of behavioral intention ($\beta = 0.328$, $p = 0.001$). Participants described this immersive-affective link clearly: "*With the headset I felt much more inside the lab, like I was really there, which made me enjoy it a lot more*" (P08). Enjoyment in turn increased flow: "*Once I got into it, I was fully absorbed, I lost track of time and just focused on the tasks*" (P21). This sequence illustrates how immersive qualities drive affective experiences that cascade into a state of flow, ultimately shaping users' acceptance of the virtual lab technology.

Rational Path. Perceived realism predicted credibility ($\beta = 0.438$, $p < 0.001$) and trustworthiness ($\beta = 0.283$, $p = 0.002$). Of these, credibility significantly predicted perceived usefulness ($\beta = 0.265$, $p = 0.015$), while trustworthiness showed no downstream effects. Usefulness, in turn, predicted behavioral intention ($\beta = 0.307$, $p < 0.001$). Participants reflected on this cognitive evaluation route, noting, for instance: "*The more realistic the avatar looked, the more I trusted what he said about the lab*" (P2). Others emphasized the link to usefulness: "*Because it seemed credible, I felt the information would actually be helpful for making a decision about the lab*" (P14). These findings support a cognitive evaluation pathway in which perceived realism translates into judgments of credibility and utility that contribute to user technology acceptance, albeit less strongly than affective responses.

Inhibitors. The hypothesized negative pathways from physical discomfort ($\beta = -0.103$, $p = 0.407$) and muscular strain ($\beta = -0.004$, $p = 0.974$) to behavioral intention were not significant. Thus, ergonomic strain did not meaningfully inhibit acceptance in this context. As participants explained: "*The headset was a bit heavy, but it didn't stop me from wanting to use the system*" (P10). Another commented: "*Even though I felt some neck strain, it didn't change whether I'd use it again*" (P27).

In summary, Model 2 reveals that technology acceptance arises from two partially independent mechanisms: an experiential path, where perceived immersion drives a sense of presence, enjoyment, and flow, and a rational path, where perceived realism drives credibility and usefulness. Both paths converge on behavioral intention, though the affective route exerts a stronger influence than the rational one.

4.3 Model 3: Flow-Mediated Task Experience Model

Model 3 (see Figure 6) examined whether flow states and empathy toward the avatar mediate the relationship between metaverse characteristics and acceptance of virtual lab technology. The model recorded strong overall performance with an average $R^2 = 0.379$, with particularly strong fits for enjoyment ($R^2 = 0.533$, $F(4, 115) = 32.825$, $p < 0.001$) and usefulness ($R^2 = 0.559$, $F(3, 116) = 49.042$, $p < 0.001$).

Metaverse Characteristics → Flow States and Empathy. Both perceived immersion and perceived realism predicted dimensions of flow: Perceived immersion significantly predicted absorption ($\beta = 0.346$, $p < 0.001$) and time distortion ($\beta = 0.286$, $p = 0.003$), while perceived realism predicted focus ($\beta = 0.291$, $p = 0.006$) and absorption ($\beta = 0.286$, $p = 0.003$). Perceived realism also predicted empathy ($\beta = 0.279$, $p = 0.009$) towards the avatar. Participants described these effects directly: "*When it felt more real, I was able to focus better ... and I felt more compassionate*" (P16). Another noted: "*With the headset I got absorbed quickly, I didn't notice the time passing*" (P9). Together, these results show that metaverse characteristics shape both experiential (flow) and social (empathy) mechanisms.

Flow States and Empathy → Task Experience. Flow and empathy exerted broad effects on task-related outcomes. Focus

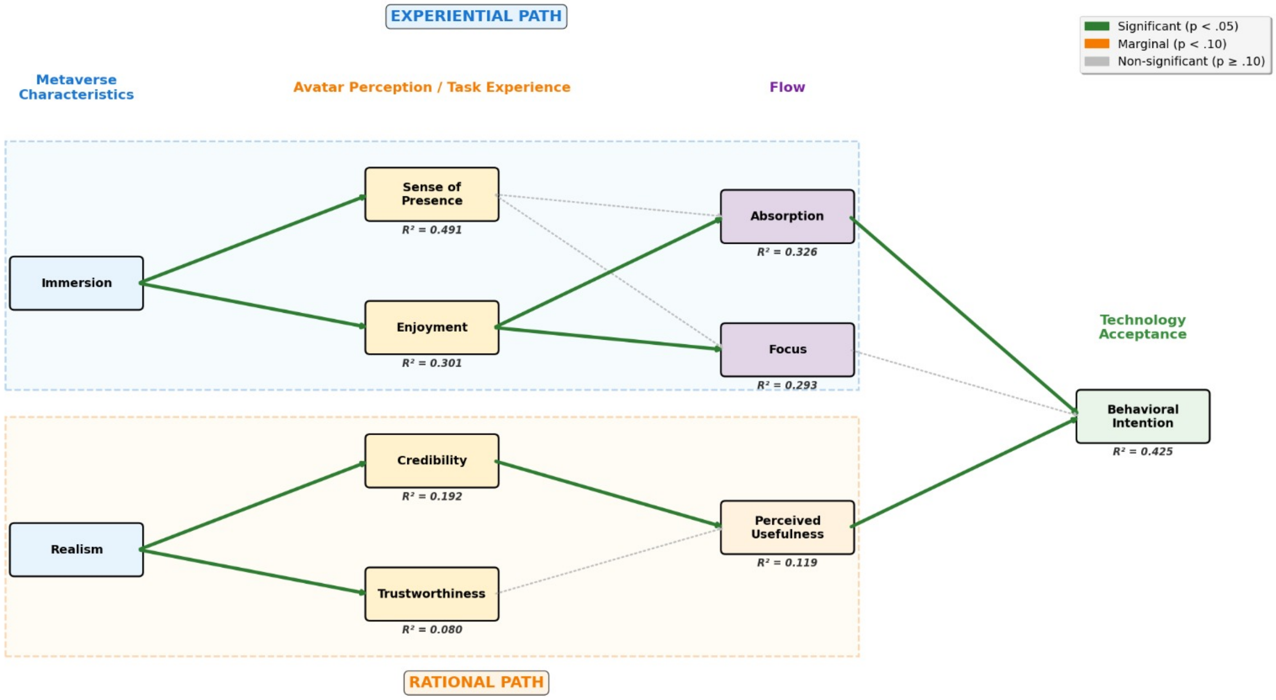

Figure 5: Results from Model 2: Dual-Path Processing. On the one hand, the *experiential path* demonstrates that perceived immersion drives enjoyment, which in turn leads to flow states and behavioral intention. On the other hand, the *rational path* shows perceived realism shapes credibility and usefulness, contributing to behavioral intention. Ergonomic strain (inhibitors) did not significantly affect technology acceptance, so they were omitted from the figure due to parsimony.

predicted confidence ($\beta = 0.261$, $p = 0.016$) and motivation ($\beta = 0.227$, $p = 0.020$), while absorption predicted enjoyment ($\beta = 0.268$, $p = 0.003$), and time distortion predicted motivation ($\beta = 0.240$, $p = 0.004$) and enjoyment ($\beta = 0.165$, $p = 0.031$). Empathy, in contrast, predicted confidence ($\beta = 0.347$, $p < 0.001$), motivation ($\beta = 0.335$, $p < 0.001$), and enjoyment ($\beta = 0.390$, $p < 0.001$). As one participant put it: "*I felt like the professor really cared about explaining things, and that made me more confident in the lab*" (P12). Another emphasized: "*I enjoyed the tour more when I could empathize with the virtual professor and when it felt more human*" (P25). These findings suggest that flow and empathy jointly support stronger task experiences, with empathy exerting a particularly consistent effect on outcomes.

Task Experience → Technology Acceptance. Task enjoyment was the strongest downstream predictor, exerting a large effect on behavioral intention ($\beta = 0.609$, $p < 0.001$) and a medium effect on perceived usefulness ($\beta = 0.417$, $p < 0.001$). Confidence also significantly predicted usefulness ($\beta = 0.381$, $p < 0.001$). Participants linked these experiences directly to acceptance: "*I enjoyed the lab tour, so I would definitely use this technology again*" (P18). Similarly: *Feeling confident during the task made me believe the system was actually useful*" (P07). Motivation, however, showed no direct effect on acceptance of virtual lab technology.

In summary, Model 3 demonstrates flow states and empathy as key mechanisms linking perceived immersion and perceived realism to technology acceptance. Ultimately, enjoyment is the strongest driver of virtual lab technology acceptance, emphasizing the importance of affective experience in task-focused metaverse environments.

4.4 Integrated Model: Virtual Lab Acceptance Model

The integrated model (see Figure 7) provides the most comprehensive account of how metaverse characteristics shape user acceptance of the virtual lab. The overall model performance was strong, with explained variance reaching $R^2 = 0.54$ for task enjoyment, $R^2 = 0.56$ for usefulness, and $R^2 = 0.51$ for behavioral intention.

Experiential Path. Perceived immersion served as the main entry point to experiential mechanisms. It strongly predicted empathy ($\beta = 0.354$, $p < 0.001$) and behavioral naturalness ($\beta = 0.479$, $p < 0.001$) of the avatar. Among these, only empathy exerted a downstream effect, predicting both task enjoyment ($\beta = 0.374$, $p < 0.001$) and motivation ($\beta = 0.324$, $p < 0.001$). Participants often described how perceived immersion increased affective connections: "*With the headset I felt like the professor was really talking to me, not just a program*" (P03). Another noted: "*I enjoyed the experience more when I felt some empathy toward the avatar*" (P19). Subsequently, enjoyment is a dominant driver of technology acceptance, predicting both usefulness ($\beta = 0.417$, $p < 0.001$) and behavioral intention ($\beta = 0.498$, $p < 0.001$). These results from the

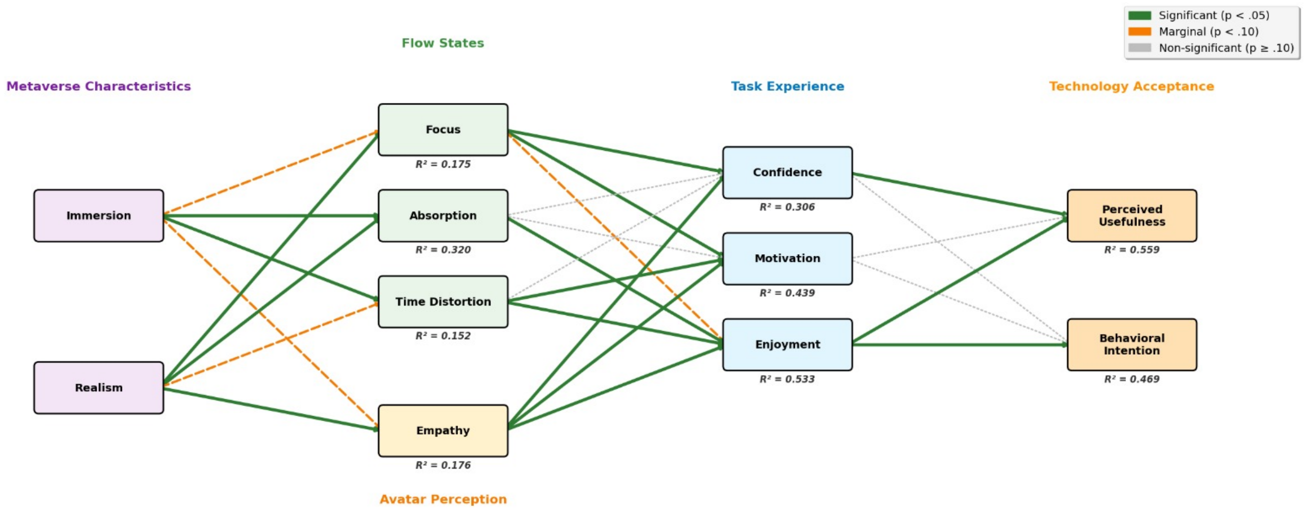

Figure 6: Results from Model 3: Flow-Mediated Task Experience. Perceived immersion and perceived realism predict flow states and empathy, which shape task confidence, motivation, and enjoyment. Task enjoyment is the dominant predictor of technology acceptance, driving both perceived usefulness and behavioral intention.

experiential path indicate that perceived immersion influences positive affective appraisals, which translate into virtual lab acceptance primarily through enjoyment.

Rational Path. Perceived realism influenced cognitive evaluations of the avatar. It significantly predicted credibility ($\beta = 0.438$, $p < 0.001$) and trustworthiness ($\beta = 0.283$, $p = 0.002$). Of these, only credibility was the stronger mediator, positively influencing task confidence ($\beta = 0.261$, $p = 0.011$), which then predicted usefulness ($\beta = 0.381$, $p < 0.001$). Participant P11 remarked, "*The more realistic the avatar looked, the easier it was to believe what it was saying, so I felt I could trust the information more.*" However, usefulness itself did not significantly predict behavioral intention ($\beta = 0.087$, $p = 0.384$), suggesting that cognitive evaluations are less decisive than affective mechanisms.

Flow as Amplifier. Flow states further reinforced both pathways. Perceived immersion contributed to absorption ($\beta = 0.346$, $p < 0.001$) and time distortion ($\beta = 0.247$, $p = 0.021$), while perceived realism also contributed to absorption ($\beta = 0.286$, $p = 0.002$) and focus ($\beta = 0.291$, $p = 0.006$). These flow states, in turn, enhanced task experiences: absorption predicted enjoyment ($\beta = 0.238$, $p = 0.010$); focus predicted confidence ($\beta = 0.264$, $p = 0.020$) and motivation ($\beta = 0.226$, $p = 0.021$); time distortion predicted enjoyment ($\beta = 0.174$, $p = 0.023$) and motivation ($\beta = 0.246$, $p = 0.004$). Notably, absorption also directly predicted behavioral intention ($\beta = 0.202$, $p = 0.033$), complementing the role of task enjoyment. This suggests that flow amplifies both experiential and rational effects on the acceptance of virtual lab technology. P14 described this effect: "*I was so absorbed that I forgot I was in VR–that made me think I could actually use this in real life*". Similarly, P27 commented: "*Time passed quickly, and that made the experience more motivating*".

The VLAM suggests that while both rational and experiential mechanisms are important, acceptance is primarily driven by affective responses amplified through the experience of flow. In particular, task enjoyment consistently showed as the strongest predictor of behavioral intention for virtual lab acceptance.

5 Discussion

5.1 Interpretation of Model Results

The results from all three conceptual models consistently demonstrate that perceived immersion and perceived realism are influential factors in driving positive UX during metaverse lab visits, advancing HCI research in this area. The progression from technical features to perceptual outcomes to behavioral intentions appears robust across different model configurations. In particular, task enjoyment is a significant predictor of behavioral intention in both Model 1 and Model 3, suggesting that this is a particularly stable and important pathway regardless of the model specification.

In all three models, affective responses are more predictive than purely cognitive evaluations. Model 2's structure explicitly demonstrates this, with the affective pathway (perceived immersion → presence/enjoyment → flow) showing stronger effects than the cognitive path (perceived realism → credibility/trustworthiness → usefulness). This pattern is corroborated by Model 1, in which empathy-driven avatar perception has a stronger effect on task experience than cognitive evaluations of perceived realism, with its impact on enjoyment and confidence outweighing that of credibility or trustworthiness. In a similar vein, the findings suggest that users' flow experience helps explain how initial perceptions connect to final outcomes. The flow-mediated model (Model 3) clarifies that metaverse characteristics (perceived immersion and perceived realism) first induce flow states, which predict the task experience (enjoyment, motivation). Flow operates as a separate

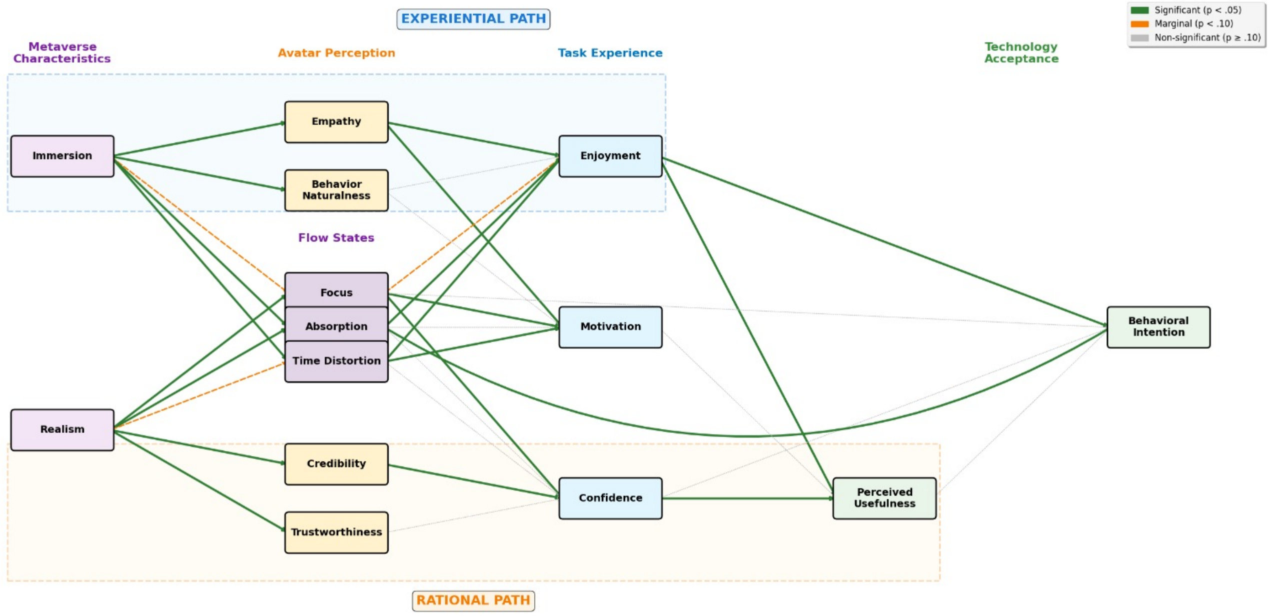

Figure 7: Results from the integrated model (VLAM). The experiential path (perceived immersion → empathy/naturalness → enjoyment/motivation) dominates technology acceptance. The rational path (Perceived realism → credibility → confidence/usefulness) plays a supporting role. Flow states amplify both pathways by strengthening task experiences and behavioral intention.

pathway alongside avatar perception (empathy), contributing to a positive UX and supporting acceptance of virtual lab technology.

Overall, the three models each captured different perspectives on metaverse UX, with Model 1 emphasizing avatar perceptions, Model 2 suggesting dual processing pathways, and Model 3 testing the dynamics of flow states. Based on these findings, the integrated VLAM model synthesizes the three perspectives by positioning flow states as psychological amplifiers that strengthen both cognitive and affective pathways in technology acceptance. Specifically, the model incorporates (1) an experiential pathway, in which perceived immersion drives avatar empathy and behavioral naturalness as the central levers of acceptance, (2) a rational pathway, in which perceived realism enhances avatar credibility and trustworthiness but plays a more supporting role, and (3) flow states (focus, absorption, time distortion), which emerge from both perceived immersion and perceived realism and amplify the impact of avatar perceptions on task experiences (confidence, enjoyment, motivation). These task experiences then converge on perceived usefulness and behavioral intention. The VLAM thus suggests that virtual lab acceptance requires not only technical quality but also the activation of flow states that intensify both cognitive evaluations and affective responses.

5.2 Contributions to HCI Research

Beyond entertainment and gaming applications, the HCI research community has increasingly called for investigations of “serious” and “productive” applications of immersive technologies [1, 15, 51, 73, 117, 130]. Our research *contributes* to this important HCI agenda by examining virtual lab tours through LLM-powered avatars in the metaverse as a concrete use case for academic communities. Given the globalized academic employment landscape, physical lab visits are costly, logistically demanding, and burden the environment. In contrast, conventional substitutes such as websites, informational brochures, or recorded video walkthroughs fail to provide the interpersonal interaction that characterizes face-to-face lab visits. Our research suggests how metaverse platforms with LLM-powered avatars may help address some limitations of conventional digital substitutes by enabling more interactive and socially grounded virtual lab tour experiences.

Our findings *extend* prior HCI, avatar, and metaverse research by clarifying how perceived realism and perceived immersion translate into technology acceptance through layered psychological mechanisms. While the individual relationships we observe are largely consistent with prior work, our contribution integrates these mechanisms into a unified explanatory framework instead of examining them in isolation. Our findings corroborate earlier work showing that perceived realism can strengthen credibility and trust [39, 67, 88] and that immersive displays enhance presence and engagement [18, 71, 125], while also reinforcing evidence that behavioral cues such as voice and gesture are as critical as visual fidelity for perceived realism [2, 79, 85, 134].

At the same time, our results *complement* previous HCI work by specifying the mechanisms underlying technology acceptance in LLM-mediated metaverse contexts. As opposed to finding isolated effects, we demonstrate that metaverse characteristics propagate through two interlinked pathways: an experiential path (in which perceived immersion increases empathy and enjoyment that strongly predict acceptance) and a rational path (in which perceived realism enhances credibility and confidence but plays a more supporting role). Flow states amplify both pathways, strengthening the translation of technical features into task experiences and, ultimately, behavioral intention. This extends acceptance research [30, 46, 47] by foregrounding experiential mechanisms in LLM-mediated, task-focused metaverse contexts.

Our findings also *refine* previous established claims in several areas. Presence did not consistently predict downstream outcomes, suggesting its impact may depend on affective or flow states instead of being a direct driver [78]. Similarly, while VR discomfort and ergonomic strain are well documented [61, 63], these did not significantly inhibit acceptance in our study, indicating that engagement may offset moderate strain. Furthermore, although the theory of uncanny valley effects cautions against hyperrealism [82, 112], our data shows that in virtual lab tour and expert-avatar contexts, higher realism primarily increased credibility and trustworthiness. Overall, the findings suggest designing metaverse systems that prioritize empathy, flow, and enjoyment.

An additional lens for interpreting these findings is *plausibility* [114], understood here as the extent to which users experience the avatar as a believable social and professional actor within the interaction context. While plausibility is not typically treated as an explicit construct in avatar research, prior HCI work has examined closely related dimensions, such as credibility, trustworthiness, social presence, and behavioral coherence [39, 88]. Although plausibility was not measured as a separate variable either in this study, our results suggest that it can be interpreted as an emergent outcome of the mechanisms captured in VLAM: avatar realism contributes through credibility and confidence, while perceived immersion supports believability through empathic engagement and flow. From this perspective, plausibility does not arise from visual realism alone, but from the coherent alignment of embodiment, behavior, and interaction dynamics over time.

The results also reveal broader opportunities for metaverse deployment in academic and professional contexts. Virtual lab tours can be implemented asynchronously and at scale, with virtual professor avatars capable of responding to inquiries in real time. This points to potential for increasing research lab accessibility, especially for populations facing financial, mobility, or geographical barriers, such as students and collaborators from the Global South. Virtual labs also support sustainability objectives, an increasingly prominent focus within HCI [29, 44], reducing reliance on air travel. (Although LLMs do consume electrical energy, their environmental impact remains minimal compared to intercontinental flights.) Simultaneously, they enable labs to better cope with the increasing demand for visits and student recruitment activities.

5.3 Design Implications

Our findings, especially from the integrated model VLAM, reveal that user acceptance is primarily driven by the experiential path (perceived immersion → empathy → enjoyment), supported by the rational path (perceived realism → credibility → confidence), with flow states amplifying both paths. Within the scope of short virtual lab tours studied here, this structure motivates several actionable design implications for virtual lab tours and related metaverse applications using avatars, proposed as follows.

Strengthen the experiential path by increasing empathy. Because empathy was the strongest predictor of enjoyment and motivation, avatars could be designed to communicate warmth, responsiveness, and relatability. This can be achieved through interaction patterns that make understanding explicit, such as brief reflective acknowledgments, consistent reuse of the user's own terms, and short summaries that confirm understanding before providing detailed explanations, alongside a conversational tone, context-sensitive answers, and maintaining subtle non-verbal cues (e.g., nodding, attentive gaze) that signal understanding. Given empathy's central mediating role in VLAM, such "conversational alignment" behaviors provide a concrete lever for designers to prioritize, even when other aspects of the experience (e.g., realism or immersion modality) vary.

Use realism selectively to support the rational path. Realism improved credibility and, through confidence, indirectly contributed to perceived usefulness. This suggests that design could emphasize realism cues that are directly interpretable as competence and trustworthiness, such as high-fidelity facial expressiveness, stable gaze/attention behavior toward the user, consistent lip-speech synchronization, and coherent nonverbal timing. Conversely, designers may avoid investing in purely cosmetic realism that is not behaviorally coherent (e.g., high visual fidelity paired with unnatural timing or mismatched lip-sync), as such inconsistencies are unlikely to strengthen credibility even if the avatar looks more realistic.

Design for flow to amplify both pathways. Absorption and time distortion strengthened the impact of both empathy (via the experiential path) and credibility (via the rational path) on acceptance, even directly predicting behavioral intention in some cases. To encourage flow, designers could consider reducing interaction friction (e.g., minimizing response delays and simplifying navigation) and embedding elements that sustain focus (e.g., clear conversational turn-taking cues, structured progression through lab zones guided by the avatar, and multimodal alignment among speech, embodiment, and spatial context).

Balance resources across experiential and rational features. Since both perceived immersion and realism contributed to acceptance through different mechanisms, design may benefit from avoiding over-investing in one while neglecting the other. For example, coupling immersive features like spatial audio and embodied navigation with credibility-supporting cues (accurate terminology, domain-specific context) could enhance both the experiential and rational pathways. Designers could operationalize this implication by allocating features according to the target mechanism, prioritizing empathy- and flow-supporting interaction quality for engagement, while using realism selectively when credibility and confidence are important.

5.4 Limitations and Future Work

This study presents new evidence on how avatar realism and immersion modality influence UX mechanisms that lead to the acceptance of virtual lab technology provided by LLM-powered avatars, advancing research in this area for the HCI community. However, some limitations point to directions for future research.

User populations. The study recruited 30 university researchers, mostly with STEM backgrounds. This sample was appropriate for the lab tour scenario, but it can limit the generalizability of the results to broader user groups or professional contexts. Future research should replicate the study with more diverse populations to examine whether the identified mechanisms hold across different user populations using, e.g., systematic representative designs [27]. Familiarity is another important factor: our participants were not familiar with the lab or the professor. It remains an open question whether recognition of visual and vocal cues would amplify realism and empathy or instead evoke uncanny effects through mismatched expectations, which is consistent with the mere-exposure effect [132].

Task specificity. We examined an academic lab tour as our metaverse context. While useful as a professional metaverse scenario, results may not directly transfer to other contexts where avatars play different roles, such as collaborative teamwork, training, or customer services [96]. Although the study used a single virtual lab tour application with short (5-minute) exposures per condition, it included four distinct lab zones and repeated measures across four conditions, providing variation in content and interaction context within the controlled tour setting. Further studies should compare VR contexts and tour designs (e.g., different labs and longer tours) to assess generalizability of the mechanisms identified in this study, stability over repeated use, and sensitivity to content and duration.

Exposure effects. The study employed a four-condition within-subject protocol lasting approximately 85 minutes. Although we counterbalanced condition order using a Latin Square, repeated exposure may still have introduced learning, habituation, or fatigue effects across conditions (e.g., participants becoming more fluent with the controls and interaction style, or experiencing reduced attention/energy over time). Future work could mitigate these effects by shortening sessions, adding longer breaks, using between-subject designs for key comparisons, or explicitly modeling session order and time-on-task as covariates to separate experience effects from the impacts of realism and immersion.

Measurement and analysis scope. Our data consisted of quantitative survey responses, qualitative open-ended survey entries, survey think-alouds, and interviews. We primarily analyzed quantitative self-report measures in relation to our conceptual models, while qualitative materials were used *selectively* to contextualize and triangulate the key quantitative pathways, with illustrative excerpts chosen by reviewing transcripts for statements that directly referenced focal constructs in the models and aligning them with the corresponding results. As we did not conduct a full systematic qualitative analysis in this paper, these excerpts should be interpreted as contextual evidence. Future work could report a systematic thematic analysis of qualitative data to offer a deeper examination of UX. Future work could also incorporate behavioral and physiological measures, such as interaction logs, eye-tracking, and physiological signals [43], to further validate and complement self-reported data. In particular, logging interaction behaviors (e.g., question counts, dialogue length, and navigation patterns) would enable testing whether usage traces mediate links from perceived immersion/realism to behavioral intention.

Experimental manipulations. Our manipulation of realism was limited to specific implementations of metaverse technologies. Other possible approaches to realism, or combinations of varying levels of visual and audio fidelity, were not examined. Prior work on uncanny-valley [19, 28] indicates that such effects can unfold in subtle and nonlinear ways. Future studies should therefore adopt more fine-grained manipulations, varying not only appearance and audio fidelity, but also behavioral realism such as gesture quality and responsiveness. In addition, future work could more systematically assess perceived coherence between the avatar's intended identity (e.g., an expert professor) and the LLM-driven behavior across interaction turns (e.g., consistency of role-appropriate tone, expertise display, and turn-taking), as such coherence likely contributes to believability and credibility beyond surface fidelity alone.

Modeling approach. The study employed path analysis to examine the relationships between metaverse characteristics, UX mechanisms, and technology acceptance. Although this approach allowed us to compare alternative conceptual models with a relatively small sample, it also has limitations. Path analysis assumes linear, directional relationships and does not account for reciprocal effects or latent constructs [66]. In addition, because our models were estimated over observed variables (instead of latent factors), measurement error in the self-report items is absorbed into the path estimates, which can attenuate coefficients and reduce the precision of mediated effects. Furthermore, since the candidate models were not preregistered, VLAM should be interpreted as a theory-driven yet exploratory framework that motivates future confirmatory validation. As such, our models necessarily simplify the complexity of immersive experiences and may overlook feedback loops or unmeasured mediators. Future work could validate VLAM using larger samples and SEM [121], enabling tests of alternative mechanisms, reciprocal paths, and latent variable structures.

Technology constraints. Even with state-of-the-art platforms such as ConvAI, technical limitations remained. Delays in system response and occasional inaccuracies sometimes disrupted interaction quality and influenced UX [32]. Additionally, issues with the physical comfort of the VR headset were frequently mentioned. As a result, research on immersive avatars is still constrained by the maturity of both software infrastructures and hardware design. Future work should investigate whether advancements in LLM responsiveness and device ergonomics can enhance the UX mechanisms identified in this study, thereby strengthening overall technology acceptance.

Risks, accessibility, and deployment considerations. LLM-powered avatars raise broader concerns that extend beyond immediate UX outcomes. Generated responses may contain inaccuracies or reflect biases [74], and authoritative-looking expert avatars may induce over-trust, especially in educational contexts where users may accept information uncritically [16]. Design safeguards such as transparency cues, confidence calibration, and clear boundaries of competence are therefore essential [64, 65]. Accessibility and inclusion are also central to deployment: Headset-based experiences may exclude users due to discomfort, sensory impairments, or hardware access constraints, motivating desktop-based and multimodal interaction alternatives [83]. Finally, virtual lab tours raise questions about how such systems complement human interaction, how they are integrated into existing educational practices, and how responsibilities for accuracy, maintenance, and ethical use are assigned [35, 126]. Future work should examine these factors alongside UX mechanisms to support responsible deployment of avatars in learning and professional settings [21, 120].

6 Conclusion

This research investigated how metaverse characteristics, specifically avatar realism and immersion, shape UX mechanisms that drive technology acceptance of virtual lab tours with an LLM-powered avatar. Using our integrated path analysis model, VLAM, we demonstrated that acceptance can originate from two pathways: an experiential path, where immersion drives empathy toward the avatar and task enjoyment as the primary levers of adoption, and a rational path, where realism strengthens avatar credibility and task confidence, playing a supporting role. Flow states amplify both pathways by intensifying task experiences and ultimately leading to technology acceptance of the virtual lab tour. Overall, the lab tour scenario illustrates the broader potential of metaverse technologies and LLM-powered avatars to expand access to research environments, providing scalable and sustainable alternatives to in-person visits for students, collaborators, and other stakeholders. Looking ahead, research and development of virtual labs with LLM-powered avatars should focus on advancing avatar responsiveness, flow-inducing design features, and scalable deployment models. These HCI efforts can help expand virtual labs into robust, accessible, and impactful tools for education, collaboration, and global research engagement.

GenAI Usage Disclosure

During the preparation of this work, the author(s) used OpenAI's ChatGPT (GPT-5) to support summarization and language editing of author-written text. The tool was not used for generating research content, data, or results. After using this tool, the author(s) carefully reviewed and edited the content, and take full responsibility for the final manuscript.

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A Facilitator Protocol

This appendix provides the facilitator protocol used during study sessions to ensure procedural consistency across participants.

Preparation

1. Distribute the consent form and privacy notice; allow participants time to review and sign.
2. Open the background survey in Qualtrics in an incognito browser window. Log the participant ID, then let participants complete the survey.
3. Record session details in the "Experiment tracker" sheet.

Briefing

1. Deliver task instructions: "You will visit a research lab in a virtual reality environment. Imagine you are a researcher considering joining this lab. Your task is to explore and learn more about the lab, including what research is done here, how the lab operates, and who is involved in running it. In the environment, you will meet an avatar modeled after the professor leading the lab. He is your lab guide. You are encouraged to freely interact with the avatar to gather information for your task."
2. Ask: "Are you clear? Do you have any questions?"
3. Provide technical instructions:
   - Desktop VR: Press "T" to talk, release when finished; use `WASD` keys to move.
   - Headset VR: Press "A" on right controller to talk, release when finished; use thumbsticks (left=move, right=rotate); if stuck, move head + thumbsticks.

Condition Execution

1. Cross-check the assigned condition order in the "Experiment tracker" sheet, and prepare the correct scene in VR accordingly.
2. Start each condition with a 5-minute timer; stop participant when time ends.
3. After each condition, open the post-condition survey in Qualtrics, log participant ID + condition, and let the participant complete it.
4. Encourage think-aloud: "Please speak aloud why you choose the answer, and any related thoughts coming to mind."
5. Start audio recording for the session. Save with filename `ParticipantID_Condition` and upload to the Drive folder.
6. Repeat for all four conditions.

Post-Condition Interview

1. Conduct a semi-structured interview (see below for themes/prompts).
2. Start audio recording; save as filename `ParticipantID_interview` and upload to Drive folder.
3. Record notes in the "Interview notes" folder.
4. Add any notable observations to the "Moderator Observations" sheet.

Interview Guide

- **Engagement:** Which version did you like best? Why? When did you feel most immersed or disengaged?
- **Credibility:** How believable were the avatars? Any moments that felt unnatural?
- **Applicability:** Could you see this system used in real learning/work? What changes would improve it?
- **Emotional Connection:** Did you feel a connection to the avatars? What made you feel that way? How avatar or distant did it feel?
- **Wrap-up:** Any other thoughts or standout moments from the experience?

B Post-Condition Survey

The post-condition survey was administered in Qualtrics immediately after each of the four experimental conditions. The full survey flow and exact wording of all items are reported here. Randomization was enabled both across construct blocks (i.e., avatar perception, task experience, flow, technology acceptance, and ergonomic strain) and across statements within each block.

B.1 Participant ID and Condition

- *Participant ID (logged by moderator)* (open text)
- *Condition (logged by moderator)* (HR–VR / LR–VR / HR–Web / LR–Web)

B.2 Manipulation Check

Please indicate how much you agree or disagree with the following statements about your experience in this condition.

- T*he experience felt like I was actually in the lab environment.* (7-point Likert)
- *The avatar felt like a real human.* (7-point Likert)

B.3 Avatar

The following questions are about the ***AVATAR****, not about the system or about the task. The avatar is the character you interacted with.*

- *Ok, I understand.* (single choice)

Avatar Short Scale

Please indicate how much you agree or disagree with the following statements based on your recent interaction with the avatar.

- *I felt like I understood this avatar.* (7-point Likert)
- *I would interact with this type of avatar in the future to learn about different things.* (7-point Likert)
- *I trusted what the avatar said to me.* (7-point Likert)
- *The avatar felt present in the same space as me.* (7-point Likert)
- *The avatar looked like a real human.* (7-point Likert)
- *The avatar sounded like a real human.* (7-point Likert)
- *The avatar seemed credible and believable.* (7-point Likert)
- *The avatar communicated clearly.* (7-point Likert)
- *Something about the avatar felt off or unnatural.* (7-point Likert)
- *The avatar seemed to have its own thoughts and intentions.* (7-point Likert)
- *The avatar's mannerisms and behaviors seemed natural.* (7-point Likert)
- *I found the avatar convincing in its role.* (7-point Likert)

Please elaborate on your answers, especially those that you had a strong opinion about. (open text)

B.4 Task

The following questions are about the ***TASK****, not about the system or about the avatar. The task is what you were doing (i.e., learning about the lab).*

- *Ok, I understand.* (single choice)

Task experience

Please indicate how much you agree or disagree with the following statements about your experience performing the lab exploration task.

- *I was motivated to learn about the lab.* (7-point Likert)
- *I enjoyed learning about the lab.* (7-point Likert)
- *I feel confident in my learning about this lab.* (7-point Likert)

Flow

Please indicate how much you agree or disagree with the following statements about your sense of flow during the interaction.

- *I was completely focused on the interaction.* (7-point Likert)
- *I felt totally absorbed in what I was doing.* (7-point Likert)
- *Time seemed to pass quickly during the interaction.* (7-point Likert)

Please elaborate on your answers, especially those that you had a strong opinion about. (open text)

B.5 System Usage

The following questions are about the ***SYSTEM****, not about the avatar or about the task. The system is the hardware and software environment you interacted with.*

Technology Acceptance Model

Please indicate how much you agree or disagree with the following statements about the system you used to interact with the avatar.

- *Using the system helped me learn about the lab.* (7-point Likert)
- *It was easy to interact with the system.* (7-point Likert)
- *I would like to use this type of system in future learning or training experiences.* (7-point Likert)

Ergonomic Strain

Please indicate how much you agree or disagree with the following statements about your physical comfort during the interaction.

- *I experienced physical discomfort during the interaction with the system.* (7-point Likert)
- *The interaction with the system caused noticeable strain on my body.* (7-point Likert)
- *My eyes felt tired or strained during or after using the system.* (7-point Likert)
- *Carrying out the task using this system required a lot of physical effort.* (7-point Likert)

Please elaborate on your answers, especially those that you had a strong opinion about. (open text)