

Analysis of the Influence of Metaverse-Based Learning Environments and Spatial Learning Intelligence on Experiential Competence Development, Mediated by Immersive Interaction Quality and Presence Perception Strength

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Abstract

The digital transformation of higher education in the Society 5.0 era drives the adoption of immersive technologies such as the edu-metaverse to replace conventional 2D online learning systems. However, the internal mechanisms of students in converting this technological sophistication into practical competencies still require empirical validation. This study aims to analyze the effects of the Metaverse-Based Learning Environment (M-BLE) and Spatial Learning Intelligence (SLI) on students' Experiential Competence Development (ECD), while examining the mediating roles of Immersive Interaction Quality (IIQ) and Presence Perception Strength (PPS). The quantitative research method employed is Structural Equation Modeling (SEM) based on SmartPLS 4. Data were gathered via online questionnaires from 250 higher education students with learning experiences in the metaverse ecosystem. The results indicate that M-BLE and SLI exert positive and significant effects on IIQ and PPS, with SLI yielding the most dominant cognitive contribution in shaping the interaction quality within the virtual space. The deconstructive findings of this study reveal that M-BLE, SLI, and IIQ do not possess a significant direct effect on students' competence development (ECD). Crucially, PPS (Presence Perception Strength) is proven to act as a full mediator within the structural model. The acceleration of technological infrastructure and students' cognitive spatial intelligence can only be successfully transformed into practical competencies (leadership, problem-solving, and teamwork) if students achieve an intimate psychological sensation of "being there" within the virtual world. This study recommends that educational institutions prioritize instructional designs that trigger profound psychological presence rather than merely focusing on technical graphical luxury.

Keywords: Metaverse-Based Learning, Spatial Intelligence, Psychological Presence, Immersive Interaction Quality

INTRODUCTION

The digital transformation in higher education has reached a new stage alongside the emergence of the Society 5.0 era. Educational institutions today are not only required to move physical classrooms into conventional online learning systems but must also reform the entire instructional ecosystem to be more adaptive, interactive, and oriented toward

students' actual competencies (Jusuf et al., 2023). One of the radical instructional technology innovations offering a solution to the limitations of one-way interaction in mainstream online learning media is the edu-metaverse (Sripan & Jeerapattanatorn, 2025). Through this three-dimensional (3D) virtual space, the learning process can be accommodated beyond geographical boundaries, where users are represented by avatars to interact, collaborate, and perform practical simulations in real-time (Sabtono & Makmur, 2024).

However, despite the rapid adoption of immersive technology in campus environments, the most crucial final output remains centered on how well this technology can facilitate real experience-based student competence development (Experiential Competence Development). According to experiential learning theory, deep conceptual understanding can only be achieved if students are actively involved in a cycle of direct experiencing, reflecting, conceptualizing, and testing it out in new situations (Rahmi, 2024). Unfortunately, the implementation of metaverse-based learning often faces significant challenges due to variations in individuals' internal cognitive capacities, such as spatial intelligence in learning (Spatial Learning Intelligence). Students with visual-spatial limitations are prone to experiencing disorientation inside 3D virtual spaces, which risks creating a cognitive overload and hindering the efficiency of information processing (Salim et al., 2025).

In addition to students' internal cognitive readiness, the success of transforming technology into practical competencies is also heavily influenced by psychological aspects and technical quality during the learning process. The characteristics of the metaverse system must be capable of generating a high Immersive Interaction Quality so that multisensory communication between the user, the system, and digital objects can run smoothly without interruption (Rawas et al., 2026). This optimal interaction quality will subsequently stimulate the Presence Perception Strength, a psychological condition where students feel as though they are genuinely inside the virtual space ("being there") (Agustini et al., 2026). When this sense of presence and interaction quality are firmly established, students will respond to virtual scenarios just like real-world situations, thereby accelerating a deeper internalization of practical skills (Roy et al., 2025).

Although the potential of each aspect has been acknowledged, a significant research gap remains regarding simultaneous testing that integrates external environmental factors (Metaverse-Based Learning Environment) and internal cognitive capacity (Spatial Learning Intelligence) into a single structural model to explain experiential competence development. Most prior studies have only focused on the technical aspects of technology adoption (such as the Technology Acceptance Model/TAM) without empirically examining its contribution to students' psychomotor and professional competence outcomes.

Based on these issues, this study aims to comprehensively analyze the influence of the metaverse-based learning environment and spatial intelligence on students' experiential competence development, while positioning immersive interaction quality and presence perception strength as mediating variables. Through a Structural Equation Modeling (SEM) approach based on SmartPLS 4, this study is expected to provide theoretical novelty in the domain of educational technology and offer practical recommendations for instructional policymakers in building effective, outcome-oriented edu-metaverse ecosystems.

A metaverse-based learning environment is defined as an immersive three-dimensional (3D) virtual space that integrates digital reality technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), to create a persistent, user-based instructional ecosystem (Mhd Salim et al., 2025). Unlike conventional two-dimensional (2D) Learning Management Systems (LMS), the metaverse allows students and lecturers to be represented by avatars to interact in real-time beyond geographical boundaries (Jusuf et al., 2023).

According to Sripan and Jeerapattanatorn (2025), the primary characteristics of the edu-metaverse include persistence, interoperability, and the ability to safely simulate complex and high-risk real-world scenarios. The integration of metaverse platforms like Spatial.io in higher education has proven capable of shifting the passive learning paradigm to an active one by facilitating multidimensional collaboration spaces (Khoerunnisa et al., 2026; Sabtono & Makmur, 2024). The utilization of this virtual space provides a rich structural foundation for forming a learning experience that is more contextual and adaptive to the technological developments of the Society 5.0 era (Rawas et al., 2026).

Immersive interaction quality refers to the degree of depth, smoothness, and reciprocity of interactions that occur between the user and the system (user-to-system), virtual objects (user-to-object), and among users (user-to-user) within the digital environment (Raman et al., 2025). Within the metaverse ecosystem, this aspect is determined by technological responsiveness, graphic realism, and the system's ability to facilitate natural multi-directional communication (Aditya et al., 2024). High-quality interaction is characterized by minimal latency and a high level of learner agency in manipulating virtual instructional elements (Sripan & Jeerapattanatorn, 2025).

According to Makransky and Petersen (as cited in Raman et al., 2025), through the Cognitive Affective Model of Immersive Learning (CAMIL), immersive interaction quality is a major trigger for learners' emotional engagement and intrinsic motivation. When a metaverse learning environment is able to deliver rich interactions with minimal technical friction, students can collaborate more deeply in completing project-based tasks (Agustini et al., 2026). Therefore, this variable acts as a vital mediating bridge that transforms metaverse infrastructure readiness into a meaningful process of academic engagement.

Presence perception or the feeling of "being there" (telepresence) is defined as a psychological state where a technology user feels physically and socially located inside a virtual environment, even though their physical body is elsewhere (Raman et al., 2025). In the world of the edu-metaverse, the strength of presence perception is driven by multisensory stimuli, the use of personalized avatars, and immersive spatial embodiment (Khoerunnisa et al., 2026). Social presence also strengthens alongside students' ability to perceive emotions and closeness with peers through real-time avatar movements and interactions (Jusuf et al., 2023).

Presence perception strength has significant psychological implications for learning outcomes. Learners who experience a strong sense of presence within the metaverse tend to ignore distractions from their physical environment, thereby increasing concentration levels and optimizing long-term memory formation (Mhd Salim et al., 2025). This solid perception of presence mediates the influence of the physical-digital environment and students' spatial cognitive abilities in absorbing the essence of every simulation activity provided (Sripan & Jeerapattanatorn, 2025).

A metaverse-based learning environment is an immersive three-dimensional (3D) virtual space that integrates Virtual Reality (VR), Augmented Reality (AR), and Artificial Intelligence to create a learning ecosystem that transcends the physical limitations of traditional classrooms (Salim et al., 2025). Within this ecosystem, learners can be represented as 3D avatars, allowing them to actively interact, simulate, and explore subject matter in a safe and dynamic digital environment (Aditya et al., 2024). Post-pandemic digital disruptions have accelerated the use of virtual platforms like Spatial.io to provide a more contextual Virtual Learning Experience in higher education (Jusuf et al., 2023; Khoerunnisa et al., 2026). Integrating the metaverse into education not only addresses space and distance limitations but also triggers learners' intrinsic motivation by displaying interactive, real-world scenario visualizations (Aditya et al., 2024; Sabtono & Makmur, 2024).

Experiential competence development is rooted in Experiential Learning Theory, where knowledge and skills are constructed through the process of transforming concrete experiences into conceptual understanding and practical application (Rahmi, 2024). In the digital era, Kolb's Experiential Learning Cycle can be innovatively reconstructed inside the metaverse (Azhari et al., 2024; Salim et al., 2025). Through virtually rendered real-world simulations, learners can engage in active experimentation, reflect on the outcomes of their actions, and sharpen professional competencies such as problem-solving, teamwork, and leadership without physical risk (Aditya et al., 2024; Azhari et al., 2024). Thus, the metaverse-based environment facilitates an adaptive transfer of practical competencies that are ready to meet global workforce challenges (Rawas et al., 2026; Utami & Sitanggang, 2024).

Spatial intelligence refers to an individual's cognitive capacity to accurately perceive, analyze, manipulate, and transform visual-spatial information (Du et al., 2026). In the context of modern learning, spatial intelligence is no longer seen merely as a static innate ability, but rather as a dynamic skill that determines how effectively a learner navigates and orientates themselves within a complex digital environment. Inside the virtual space of the metaverse, students are required to comprehend geometric coordinates, object depth, and 3D spatial representations (Khoerunnisa et al., 2026).

High spatial intelligence makes it easier for students to build solid mental frameworks when faced with abstract data visualizations or structural simulations (Sripan & Jeerapattananorn, 2025). Learners with trained spatial intelligence tend to be more adaptive in leveraging the immersive features of the metaverse because they can process visual-spatial stimuli simultaneously without experiencing excessive cognitive overload, thereby directly supporting the effective reception of instructional materials (Mhd Salim et al., 2025).

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According to Makransky and Petersen (as cited in Raman et al., 2025), through the Cognitive Affective Model of Immersive Learning (CAMIL), immersive interaction quality is a primary trigger for emotional engagement and intrinsic motivation. When a metaverse learning environment is capable of delivering rich interactions with minimal technical friction, students can collaborate more deeply in completing project-based tasks (Agustini et al., 2026). Therefore, this variable acts as a vital mediating bridge that transforms metaverse infrastructure readiness into a meaningful process of academic engagement.

Spatial intelligence is one of the dimensions in multiple intelligences theory, referring to a person's mental capability to accurately perceive, analyze, manipulate, and reconstruct visual-spatial objects or information (Gardner, 2011). In instructional settings, spatial intelligence is no longer viewed as just a physical navigation capacity, but rather as an essential cognitive capacity for processing graphics-based learning media, animations, and three-dimensional (3D) modeling (Newcombe, 2020).

Learners with high spatial intelligence possess an advantage in forming mental representations of complex spatial structures without needing to see their physical form directly (Uttal et al., 2013). Conversely, learners with low spatial intelligence tend to require longer adaptation times and greater cognitive effort when faced with learning media that demand orientation mapping and visual depth perception.

Presence perception, often referred to as a sense of presence, is defined as a psychological state where a user of mediated media feels as though they are genuinely inside the virtual environment, ignoring the physical environment around them (Steuer, 1992; Biocca, 1997). In the context of educational technology—such as Virtual Reality (VR), Augmented Reality (AR), and 3D simulations—presence serves as a crucial indicator determining the effectiveness of knowledge transfer.

According to Wirth et al. (2007), the formation of spatial presence occurs through two primary cognitive stages. First, the learner builds a Spatial Situation Model based on the visual and spatial stimuli received from the media. Second, the learner unconsciously establishes the virtual environment as the primary reference point for their actions (Primary Ego-Center). When this perception of presence is strong, the learner's emotional engagement and intrinsic motivation increase significantly, which in turn positively impacts long-term memory retention (Cummings & Bailenson, 2016).

The relationship between spatial intelligence and presence perception strength can be explained by the visual-spatial information processing capacity in the brain. Learners with high spatial intelligence can construct a spatial situation model more efficiently and accurately when interacting with immersive learning media (Coxon et al., 2016). This efficiency minimizes extraneous cognitive load, allowing the remaining cognitive capacity to be fully allocated toward absorbing the material content and experiencing the immersive sensation of the virtual environment (Sweller et al., 2011).

Conversely, limited spatial intelligence capacity can hinder the formation of a spatial situation model. Learners with low spatial abilities often experience spatial disorientation inside virtual environments, triggering cybersickness symptoms such as dizziness and nausea (Chang et al., 2020). When cognitive energy is depleted simply by trying to comprehend position orientation and direction, the learner's focus on the media becomes fragmented, drastically reducing the presence perception strength (Wirth et al., 2007).

Therefore, spatial intelligence acts as an internal cognitive predictor that heavily influences how learners adapt immersive technology stimuli into a real, functional experience of presence to achieve optimal learning outcomes.

Spatial intelligence is the mental ability to accurately visualize, manipulate, and alter spatial objects or patterns. In modern learning ecosystems, this intelligence is no longer just a passive cognitive ability, but an active catalyst that enables learners to comprehend abstract concepts through visual and spatial representations (Hodgkiss et al., 2021). Learning that integrates spatial stimulation has proven to improve memory retention and complex problem-solving, as the human brain processes visual information simultaneously with the formation of cognitive maps (Newcombe, 2023). Consequently, optimizing spatial intelligence in classrooms and laboratories becomes an important foundation for the effectiveness of knowledge transfer.

Experiential learning places reflection on direct action at the center of the competence acquisition process. According to contemporary theory, competence cannot grow optimally through theoretical exposure alone; it must be formed through a cycle of active experimentation and conceptualization (Kolb & Kolb, 2022). Experiential competence development includes enhancing practical skills, adaptability to new situations, and reality-based decision-making. Recent research shows that physical and emotional involvement in experience-based activities strengthens neural connections, making the acquired competencies more sticky and applicable (McCarthy, 2024).

Spatial intelligence exerts a significant and direct influence on the success of experiential learning. When learners are faced with practical tasks—such as digital simulations, project mapping, or laboratory experiments—spatial reasoning ability acts as a bridge between abstract instructions and physical execution (Sari & Setiawan, 2023).

Learners with high spatial intelligence can perform spatial orientation and mental object manipulation rapidly, which is highly crucial in solving experience-based challenges (Wai & Rindermann, 2025).

Furthermore, in the digital era, experiential learning is frequently manifested through Virtual Reality (VR) and Augmented Reality (AR) technologies. This is where spatial intelligence plays a deterministic role; spatially proficient learners can navigate these immersive environments with minimal cognitive distortion, allowing them to focus entirely on developing the technical competencies being trained (Chien et al., 2022). Overall, spatial intelligence accelerates the process of internalizing experiences into real, ready-to-use competencies.

Developments in digital technology have transformed the learning paradigm from an information-delivery approach to one that emphasizes direct experience (experiential learning). One form of this innovation is immersive learning, an environment capable of generating a high sense of presence, engagement, and interaction through the utilization of technologies like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). In this context, immersive interaction quality is determined not only by technological sophistication but also by the learning environment's capability to build an authentic, interactive, and meaningful learning experience (Cabrera-Duffaut et al., 2024).

Immersive interaction quality comprises several main dimensions: presence, embodiment, interactivity, and engagement. Presence describes the extent to which learners feel genuinely located within the virtual environment, while embodiment shows the physical and psychological involvement of the individual when interacting with digital objects. Interactivity allows learners to actively explore the learning environment, while engagement reflects cognitive, affective, and behavioral involvement during the learning process (Mustika et al., 2026).

Various studies demonstrate that learning experiences with high interaction quality can improve learner attention, motivation, and participation compared to conventional methods. Interactive learning environments enable learners to acquire authentic experiences through real situation simulations, making the process of knowledge construction more effective (Won et al., 2022).

Beyond increasing learning motivation, immersive interaction quality also plays a role in strengthening the connection between the learning experience and competence achievement. Therefore, interaction quality is no longer seen as a mere technological characteristic, but as a pedagogical factor determining the success of technology-based immersive learning implementations (Cao et al., 2023).

Experience-based competence is an ability that develops through direct learning, reflection, exploration, and problem-solving in real situations. This approach is rooted in Experiential Learning theory, which positions experience as the primary source for forming knowledge, skills, attitudes, and professional capabilities.

In modern education, competence is no longer understood as confined to cognitive mastery; it encompasses critical thinking, communication, collaboration, creativity, problem-solving, and the ability to make decisions based on real experiences. Experiential learning environments enable learners to develop these competencies through authentic and reflective activities (Duchatelet et al., 2024).

Systematic review results show that experiential learning consistently delivers positive impacts on generic skill development, particularly communication skills, teamwork, self-regulation, and problem-solving. Authentic learning experiences offer students opportunities to link theoretical concepts with practice, resulting in deeper learning (Duchatelet et al., 2024).

Furthermore, experience-based competence develops through a cycle of concrete experience, reflection, conceptualization, and active experimentation. Thus, the quality of the learning experience is an important factor determining the level of student competence achievement (Lee et al., 2026).

The relationship between immersive interaction quality and experiential competence development can be explained through the perspectives of experiential learning and immersive learning. A learning environment with high levels of presence, engagement, and interactivity can produce a more realistic learning experience, giving students opportunities to develop competence through direct practice, exploration, and reflection.

Cabrera-Duffaut et al. (2024) explain that the use of Virtual Reality in higher education consistently contributes to the development of interpersonal competence, communication skills, cooperation, and higher-order thinking skills through deeper learning experiences.

Won et al. (2022) also found that instructional designs providing a high degree of interactivity generate greater engagement compared to passive learning. The higher the quality of interaction between the user and the virtual environment, the higher the opportunity for students to build a meaningful learning experience.

Meanwhile, Mustika et al. (2026) argue that this relationship is mediated by three primary psychological mechanisms: presence, embodiment, and engagement. These three factors reinforce the process of constructing experience, directly impacting the improvement of learning outcomes and competence development.

Thus, it can be understood that immersive interaction quality is an important determinant in forming an effective learning experience. The higher the quality of interaction perceived by the students, the greater the opportunity for experience-based competence to develop through an active, authentic, and reflective learning process.

Presence perception is a psychological condition where an individual feels genuinely located inside a technology-mediated environment, significantly reducing attention toward the real environment. Unlike immersion, which refers more to the technical characteristics of a system, presence is a subjective experience emerging from the user's interaction with the virtual environment (Wilkinson et al., 2021).

Recent literature explains that presence perception strength is influenced by visual and audio quality, interactivity, environmental realism, and the system's ability to provide natural feedback to the user. The higher the quality of these factors, the greater the likelihood of the user experiencing a deep sensation of "being there" (Jung & Lindeman, 2021).

A systematic review conducted by Krassmann et al. (2023) shows that presence perception has evolved into one of the main psychological variables in Virtual Reality (VR) learning. The study found that most educational research considers presence an important mediator between the learning experience and improved learning outcomes. However, this relationship is still influenced by media characteristics, instructional design, and learner traits.

Furthermore, Merino and Higuera-Trujillo (2023) explain that the sense of presence is influenced not only by technology quality but also by cognitive, affective, and individual characteristics. The perception of presence becomes stronger when the user can actively interact with the virtual environment, creating an experience that resembles real situations.

A recent study by Ojeda de Ocampo et al. (2026) even states that research on presence is moving from merely measuring the user's existence in a virtual environment to understanding how presence can influence thinking processes, emotional engagement, and competence achievement. This indicates that presence perception strength is an increasingly vital psychological variable in technology-based learning research.

Experience-based competence is an individual capability that develops through direct involvement in a learning activity, so that knowledge, skills, and attitudes are formed simultaneously through the process of reflecting on that experience.

This concept is rooted in Experiential Learning theory, which emphasizes that learning occurs not just through information delivery, but through concrete experience, reflection, conceptualization, and active experimentation. The development of immersive technology expands the implementation of this theory because it allows learners to acquire experiences that were previously difficult to realize in conventional environments.

Research by Mustika et al. (2026) shows that immersive learning environments generate richer learning experiences because they can integrate presence, engagement, and embodiment. Together, these three factors maximize the effectiveness of experiential learning so that student competencies develop more optimally.

In addition, Krassmann et al. (2023) found that competence enhancement in VR-based learning is not solely influenced by technology use, but primarily by the quality of the learning experience students go through during the process. The more authentic the perceived learning experience, the higher the chance of forming competencies that can be applied in real situations.

Thus, experience-based competence can be understood as the result of internalizing a learning experience that produces sustained capability changes through the active involvement of the student.

The relationship between presence perception and experience-based competence is gaining significant attention in digital learning research. High psychological presence enables students to feel part of the learning situation, so exploration, problem-solving, and reflection take place more naturally.

Krassmann et al. (2023), through a 24-year systematic review, concluded that most studies indicate a positive relationship trend between presence and learning outcomes. Although the strength of the relationship varies across contexts, presence generally enhances attention, motivation, engagement, and learning retention.

Mustika et al. (2026) explain that presence does not act directly on learning outcomes, but rather through increasing engagement and embodiment. Students with a high perception of presence tend to be more active in exploring the learning environment, interacting with learning objects, and reflecting on the experiences gained. This process ultimately yields better competence development.

Wilkinson et al. (2021) also assert that the success of immersive technology depends not on the level of immersion alone, but on the technology's ability to generate presence. In other words, the quality of the user's psychological experience is the main factor determining learning effectiveness.

A recent study by Ojeda de Ocampo et al. (2026) shows that state-of-the-art research is beginning to position presence as a predictor variable influencing the formation of learning experiences, cognitive engagement, and competence achievement. These findings reinforce the assumption that the higher the presence perception strength, the greater the opportunity for experience-based competence to develop.

Based on the synthesis of these various studies, it can be formulated that presence perception strength is an important determinant in experiential competence development because it can enhance the quality of learning interactions, student engagement, and the meaning of the experience gained during the learning process.

A metaverse-based learning environment fundamentally offers more than access to virtual space representations; it creates a learning experience mediated by the quality of interactions the user experiences. From an experiential learning perspective, the effectiveness of a virtual environment is determined by the system's capacity to deliver

natural, responsive, and meaningful interactions so that learners can actively build their learning experiences. Therefore, Immersive Interaction Quality is viewed as a mediating mechanism explaining how the characteristics of both the Metaverse-Based Learning Environment and Spatial Learning Intelligence translate into enhanced Experiential Competence Development. The higher the perceived quality of interaction, the greater the opportunity for students to engage in exploration, reflection, and knowledge application within experience-based learning contexts (Bagher et al., 2021; Sinha & D'Souza, 2023).

Beyond interaction quality, Presence Perception Strength also serves as a psychological mechanism reinforcing the relationship between the virtual environment and learning outcomes. The perception of presence (sense of presence) describes the extent to which an individual feels genuinely "inside" the virtual environment, keeping attention, emotional engagement, and cognitive processes more focused on the learning activity. Various studies show that the higher the perception of presence, the greater the learning motivation, knowledge transfer, and experiential competence development because learners treat the virtual experience as a meaningful real experience (Choi & Noh, 2021; Hameed & Perkis, 2024).

Based on these theoretical arguments, the relationships of Metaverse-Based Learning Environment and Spatial Learning Intelligence on Experiential Competence Development are expected to occur not only directly, but also through enhancements in Immersive Interaction Quality and Presence Perception Strength. A metaverse environment designed with high-quality interactions will strengthen the user's perception of presence, while spatial intelligence allows learners to leverage the virtual environment more effectively, making the learning experience more meaningful. Accordingly, this study proposes that Immersive Interaction Quality and Presence Perception Strength act as mediating variables explaining the influence of Metaverse-Based Learning Environment and Spatial Learning Intelligence on Experiential Competence Development, as formulated in hypotheses H9, H10, H11, and H12.

METHODS

Research Design and Study Area

This study uses a quantitative approach with an explanatory research design aimed at testing the causal relationships among the variables formulated in the conceptual model. The research focus is directed at analyzing the influence of Metaverse-Based Learning Environment and Spatial Learning Intelligence on Experiential Competence Development with the mediating roles of Immersive Interaction Quality and Presence Perception Strength. The quantitative approach was chosen because it allows for the objective measurement of relationships between constructs through testing a structural model based on empirical data.

The research was conducted among students at Universitas Bina Bangsa who have experience using digital learning platforms based on the metaverse, virtual reality (VR), augmented reality (AR), or three-dimensional (3D) virtual learning environments. Data collection was carried out online using electronic questionnaires during the research period. The unit of analysis in this study is the individual student participating in immersive technology-based learning activities.

Population, Sampling Technique, and Data Collection

The research population consists of university students who have participated in metaverse-based learning or immersive learning technologies. The sampling technique utilizes non-probability sampling with a purposive sampling approach, selecting respondents based on specific criteria to align with the research objectives.

The respondent criteria include: (1) active students at the higher education level; (2) having participated in metaverse-based or immersive technology learning; and (3) willing to complete the questionnaire fully. Based on the data collection process, a total of 250 questionnaires met the criteria and were deemed fit for analysis.

The research instrument was a closed online questionnaire distributed via Google Forms. Each indicator was measured using a five-point Likert scale, where 1 = strongly disagree to 5 = strongly agree. In addition to the primary data, the study also gathered demographic characteristics of the respondents as supporting information for the analysis.

Measurement Instrument and Variables

The research model comprises five latent constructs: Metaverse-Based Learning Environment (X1), Spatial Learning Intelligence (X2), Immersive Interaction Quality (Y1), Presence Perception Strength (Y2), and Experiential Competence Development (Z). All constructs were measured using reflective indicators adapted from various prior studies in accordance with the operational definitions of each variable.

Prior to testing the structural model, all indicators were evaluated through validity and reliability testing using the PLS algorithm. The evaluation was carried out in stages across three iterations (runs). In the first iteration, several indicators were eliminated because their outer loading values fell below the minimum threshold of 0.70. The second evaluation still showed one indicator that did not meet the criteria, leading to another elimination. After the third iteration, all remaining indicators met the convergent validity criteria with outer loading values > 0.70 , confirming that the measurement model was appropriate to proceed to the structural model testing stage.

Data Analysis Procedure

Data analysis was performed using Structural Equation Modeling based on Partial Least Squares (PLS-SEM) using SmartPLS software version 4. The PLS-SEM approach was selected because it is capable of testing complex relationships among latent variables, including direct and indirect effects via mediating variables.

The analysis was executed in two stages. The first stage was the evaluation of the measurement model (outer model), which included testing convergent validity using outer loading values and Average Variance Extracted (AVE), discriminant validity, and construct reliability using Cronbach's Alpha and Composite Reliability. Indicators with outer loading values below 0.70 were eliminated step-by-step until all constructs met validity and reliability criteria.

The second stage was the evaluation of the structural model (inner model). At this stage, tests were conducted for path coefficients, coefficients of determination (R^2), effect sizes (f^2), predictive relevance (Q^2), and hypothesis testing through the bootstrapping procedure. Bootstrapping was used to obtain t-statistics and p-values to determine the significance of direct and indirect (mediating) influences between the research variables. A hypothesis was accepted if the p-value was smaller than 0.05 at a 5 percent significance level.

H1: Metaverse-Based Learning Environment (X1) has a positive and significant effect on Immersive Interaction Quality (Y1).

H2: Metaverse-Based Learning Environment (X1) has a positive and significant effect on Presence Perception Strength (Y2).

H3: Metaverse-Based Learning Environment (X1) has a positive and significant effect on Experiential Competence Development (Z).

H4: Spatial Learning Intelligence (X2) has a positive and significant effect on Immersive Interaction Quality (Y1).

H5: Spatial Learning Intelligence (X2) has a positive and significant effect on Presence Perception Strength (Y2).

H6: Spatial Learning Intelligence (X2) has a positive and significant effect on Experiential Competence Development (Z).

H7: Immersive Interaction Quality (Y1) has a positive and significant effect on Experiential Competence Development (Z).

H8: Presence Perception Strength (Y2) has a positive and significant effect on Experiential Competence Development (Z).

H9: Metaverse-Based Learning Environment (X1) has a positive and significant effect on Experiential Competence Development (Z) through Immersive Interaction Quality (Y1).

H10: Metaverse-Based Learning Environment (X1) has a positive and significant effect on Experiential Competence Development (Z) through Presence Perception Strength (Y2).

H11: Spatial Learning Intelligence (X2) has a positive and significant effect on Experiential Competence Development (Z) through Immersive Interaction Quality (Y1).

H12: Spatial Learning Intelligence (X2) has a positive and significant effect on Experiential Competence Development (Z) through Presence Perception Strength (Y2).

Conceptual Framework of Adaptive Public Policy Governance for the Green Transition is presented in figure 1.

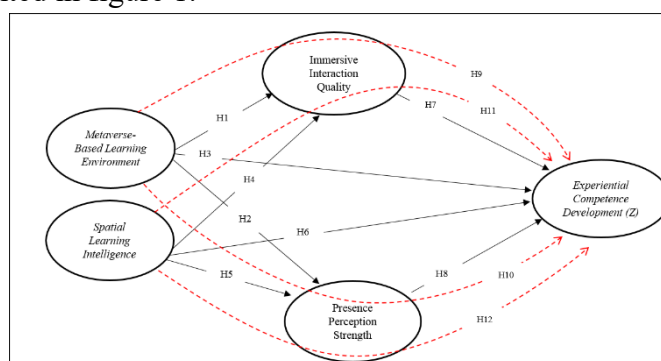


Figure 1. Research Design

Ethical Considerations

This research was conducted in compliance with ethical research principles. All respondents received information regarding the research purpose, data confidentiality, and the right to stop participating at any time without consequence. Respondent consent was given voluntarily before filling out the questionnaire.

All acquired data are strictly used for academic purposes. Respondents' identities are omitted from the research publication to maintain anonymity and information confidentiality. The data processing was carried out objectively and solely to answer the research objectives.

RESULTS

Assessment of the Measurement Model

Reliability analysis was performed using Cronbach's Alpha and Composite Reliability (CR) to examine the internal consistency of the measurement instruments used in the proposed structural framework. A construct is generally considered reliable when both

indices exceed the threshold value of 0.70, indicating satisfactory consistency among measurement indicators.

Table 1. Reliability Assessment

Construct	Cronbach's Alpha	Composite Reliability (CR)	Interpretation
<i>Metaverse-Based Learning Environment (X1)</i>	0.913	0.934	Reliable
<i>Spatial Learning Intelligence (X2)</i>	0.896	0.922	Reliable
<i>Immersive Interaction Quality (Y1)</i>	0.919	0.940	Reliable
<i>Presence Perception Strength (Y2)</i>	0.905	0.928	Reliable
<i>Experiential Competence Development (Z)</i>	0.952	0.964	Reliable

Table 1 presents the results of the reliability analysis using Cronbach's Alpha and Composite Reliability (CR) to evaluate the internal consistency of the constructs in the proposed green governance framework. The findings indicate that all constructs exceed the commonly accepted threshold of 0.70, demonstrating strong internal consistency across measurement items.

Specifically, *Metaverse-Based Learning Environment (X1)*, *Spatial Learning Intelligence (X2)*, *Immersive Interaction Quality (Y1)*, *Presence Perception Strength (Y2)*, and *Experiential Competence Development (Z)* all exhibit high reliability values, with Composite Reliability scores ranging from 0.922 to 0.964. These results confirm that the indicators consistently measure their respective latent variables without significant measurement error.

Overall, the reliability assessment suggests that the measurement instrument is stable and appropriate for capturing institutional, governance, and environmental performance constructs within the green transition framework. This provides a strong foundation for further validity and structural model analysis.

The evaluation of the measurement model was conducted to ensure that each indicator sufficiently represents its measured latent construct. Convergent validity testing was carried out through outer loading values with a minimum threshold of 0.70. The evaluation process was performed step-by-step using the PLS algorithm in SmartPLS 4.

The initial analysis results indicated that several indicators had outer loading values below the minimum threshold, leading to their elimination from the model. After three iterations, all indicators retained in the final model possessed outer loading values above

0.70, satisfying the convergent validity criteria. Thus, all indicators used in the final model are deemed capable of reflecting the latent constructs adequately and are suitable for the subsequent analysis stages.

Structural Model and Hypothesis Testing

Based on the table above, the interpretations are as follows:

Tabel 2. Structural Model and Hypothesis Testing

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/ STDEV)	P values
IIQ (Y1) -> ECD (Z)	0.010	0.008	0.053	0.195	0.845
M-BLE (X1) -> ECD (Z)	-0.048	-0.047	0.031	1.551	0.121
M-BLE (X1) -> IIQ (Y1)	0.158	0.157	0.052	3.071	0.002
M-BLE (X1) -> PPS (Y2)	0.325	0.331	0.074	4.386	0.000
PPS (Y2) -> ECD (Z)	0.935	0.936	0.012	80.041	0.000
SLI (X2) -> ECD (Z)	0.018	0.019	0.046	0.393	0.694
SLI (X2) -> IIQ (Y1)	0.822	0.825	0.044	18.609	0.000
SLI (X2) -> PPS (Y2)	0.211	0.207	0.071	2.976	0.003

The path coefficient value (Original Sample) of Metaverse-Based Learning Environment (X1) on Immersive Interaction Quality (Y1) is 0.158. This signifies that Metaverse-Based Learning Environment (X1) has a positive effect on Immersive Interaction Quality (Y1). Meanwhile, the P-value is $0.002 < 0.05$, meaning the influence is significant. Therefore, H1 is Accepted. The path coefficient value (Original Sample) of Metaverse-Based Learning Environment (X1) on Presence Perception Strength (Y2) is 0.325. This means Metaverse-Based Learning Environment (X1) has a positive effect on Presence Perception Strength (Y2). The P-value is $0.000 < 0.05$, indicating a significant influence. Therefore, H2 is Accepted.

The path coefficient value (Original Sample) of Metaverse-Based Learning Environment (X1) on Experiential Competence Development (Z) is -0.048. This indicates that Metaverse-Based Learning Environment (X1) has no direct effect on Experiential Competence Development (Z). The P-value is $0.121 > 0.05$, which means the influence is not significant. Therefore, H3 is Rejected. The path coefficient value (Original Sample) of Spatial Learning Intelligence (X2) on Immersive Interaction Quality (Y1) is 0.822. This demonstrates that Spatial Learning Intelligence (X2) has a positive effect on Immersive Interaction Quality (Y1). The P-value is $0.000 < 0.05$, showing the influence is highly significant. Therefore, H4 is Accepted.

The path coefficient value (Original Sample) of Spatial Learning Intelligence (X2) on Presence Perception Strength (Y2) is 0.211. This signifies that Spatial Learning Intelligence (X2) has a positive effect on Presence Perception Strength (Y2). The P-value is

0.003 < 0.05, which denotes a significant influence. Therefore, H5 is Accepted. The path coefficient value (Original Sample) of Spatial Learning Intelligence (X2) on Experiential Competence Development (Z) is 0.018. This implies that Spatial Learning Intelligence (X2) has a positive but weak effect on Experiential Competence Development (Z). The P-value is 0.694 > 0.05, meaning the direct effect is not significant. Therefore, H6 is Rejected.

The path coefficient value (Original Sample) of Immersive Interaction Quality (Y1) on Experiential Competence Development (Z) is 0.010. This indicates that Immersive Interaction Quality (Y1) has a positive effect on Experiential Competence Development (Z). However, the P-value is 0.845 > 0.05, which means the direct influence is not significant. Therefore, H7 is Rejected. The path coefficient value (Original Sample) of Presence Perception Strength (Y2) on Experiential Competence Development (Z) is 0.935. This means Presence Perception Strength (Y2) has a positive effect on Experiential Competence Development (Z). The P-value is 0.000 < 0.05, indicating the influence is exceptionally significant. Therefore, H8 is Accepted.

Mediation Analysis

The path coefficient value (Original Sample) of Metaverse-Based Learning Environment (X1) on Experiential Competence Development (Z) through Immersive Interaction Quality (Y1) is 0.002. The P-value is 0.853 > 0.05, indicating that the indirect effect of Metaverse-Based Learning Environment (X1) on Experiential Competence Development (Z) mediated by Immersive Interaction Quality (Y1) is not significant. Therefore, H9 is Rejected.

The path coefficient value (Original Sample) of Metaverse-Based Learning Environment (X1) on Experiential Competence Development (Z) through Presence Perception Strength (Y2) is 0.304. The P-value is 0.000 < 0.05, demonstrating that the indirect effect of Metaverse-Based Learning Environment (X1) on Experiential Competence Development (Z) mediated by Presence Perception Strength (Y2) is positive and highly significant. Therefore, H10 is Accepted.

The path coefficient value (Original Sample) of Spatial Learning Intelligence (X2) on Experiential Competence Development (Z) through Immersive Interaction Quality (Y1) is 0.009. The P-value is 0.846 > 0.05, showing that the indirect effect of Spatial Learning Intelligence (X2) on Experiential Competence Development (Z) mediated by Immersive Interaction Quality (Y1) is not significant. Therefore, H11 is Rejected.

The path coefficient value (Original Sample) of Spatial Learning Intelligence (X2) on Experiential Competence Development (Z) through Presence Perception Strength (Y2) is 0.197. The P-value is 0.003 < 0.05, confirming that the indirect effect of Spatial Learning Intelligence (X2) on Experiential Competence Development (Z) mediated by Presence Perception Strength (Y2) is positive and significant. Therefore, H12 is Accepted.

Table 3. Mediation Analysis Results

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
M-BLE (X1) -> IIQ (Y1) -> ECD (Z)	0.002	0.001	0.009	0.185	0.853
SLI (X2) -> PPS (Y2) - > ECD (Z)	0.197	0.193	0.066	2.992	0.003
SLI (X2) -> IIQ (Y1) -> ECD (Z)	0.009	0.007	0.044	0.194	0.846

M-BLE (X1) -> PPS	0.304	0.310	0.070	4.350	0.000
(Y2) -> ECD (Z)					

DISCUSSION

The Contribution of the Edu-Metaverse Ecosystem to Interaction and Psychological Perception (H1 and H2)

The structural analysis empirically proves that the Metaverse-Based Learning Environment (X1) has a positive and significant effect on Immersive Interaction Quality (Y1) ($\beta = 0.158$, $t = 3.071$, $P = 0.002$) and on Presence Perception Strength (Y2) ($\beta = 0.325$, $t = 4.386$, $P = 0.000$). These findings indicate that the more persistent, adaptive, and interactive the 3D virtual space infrastructure provided by an institution is, the stronger the depth of multisensory communication and social closeness experienced by students will be.

Theoretically, this finding strongly aligns with the characteristics of the edu-metaverse proposed by Sripan and Jeerapattanatorn (2025) as well as Jusuf et al. (2023), who state that the utilization of personal avatars and 3D simulation spaces can break the limitations of one-way interaction in conventional 2D LMS systems. The phenomenon of a strengthening psychological presence perception (sense of presence) supports the arguments of Raman et al. (2025) that multisensory stimulation inside the metaverse triggers a psychological state where users ignore real-world physical distractions and focus entirely on the virtual academic experience (being there).

The Role of Students' Internal Cognitive Capacity in Immersive Learning (H4 and H5)

A highly compelling finding in this study is the massive impact of the Spatial Learning Intelligence (X2) path coefficient on Immersive Interaction Quality (Y1), which reaches $\beta = 0.822$ ($t = 18.609$, $P = 0.000$), alongside its significant effect on Presence Perception Strength (Y2) ($\beta = 0.211$, $t = 2.976$, $P = 0.003$). This highly dominant statistical figure proves that students' internal cognitive readiness in terms of direction orientation mapping, visual depth, and mental object manipulation is a primary determinant of successful interaction inside the metaverse.

Theoretical comparison shows that these results fully support the two cognitive stages in spatial presence formation according to Wirth et al. (2007). Students with high spatial intelligence can construct a Spatial Situation Model instantly and efficiently when receiving stimuli from immersive media. Based on the Cognitive Load Theory by Sweller et al. (2011), this internal cognitive efficiency minimizes the extraneous cognitive load. Conversely, if a student's spatial intelligence is low, their remaining cognitive energy will be depleted just to avoid spatial disorientation and cybersickness symptoms (nausea/dizziness), drastically reducing interaction quality and the immersive sensation, as cautioned by Chang et al. (2020).

Deconstructing the Direct Effects on Competence Outcomes (H3, H6, H7, and H8)

The structural model test results show a surprising empirical fact: none of the exogenous variables or the first mediating variable exert a significant direct effect on Experiential Competence Development (Z). The direct paths M-BLE $\rightarrow$ ECD (H3 rejected; $P = 0.121$), SLI $\rightarrow$ ECD (H6 rejected; $P = 0.694$), and IIQ $\rightarrow$ ECD (H7 rejected; $P = 0.845$) are all non-significant. The only variable that exerts a direct, massive, and absolute influence on student competence development is Presence Perception Strength (Y2) $\rightarrow$ ECD (Z) with a coefficient of $\beta = 0.935$ and a fantastic t-statistic value of 80.041 ($P = 0.000$).

This finding provides a new theoretical contribution that deconstructs general assumptions. Advanced metaverse infrastructure (M-BLE) and superior spatial intelligence

(SLI) will never translate into real competencies (such as problem-solving, teamwork, or leadership) if students do not feel an intimate psychological presence inside the virtual space. Comparison with the Cognitive Affective Model of Immersive Learning (CAMIL) by Makransky & Petersen reinforces that immersive technology only acts as a physical medium; what drives the wheel of Kolb's Experiential Learning Cycle is the learner's deep psychological involvement. The true feeling of "being there" causes students to respond to virtual simulation scenarios just like physical reality. This is what according to Krassmann et al. (2023) triggers a sustainable internalization of practical expertise without real-world physical risks.

Analysis of the Mediation Mechanisms (H9, H10, H11, and H12)

To clarify the transformation path of variables from environmental and cognitive aspects into actual student competence, the mediation pathways (indirect effects) are classified into two main circuits:

Failure of Immersive Interaction Quality Mediation (H9 and H11): The bootstrapping procedure rejected Hypothesis 9 ($P = 0.853$) and Hypothesis 11 ($P = 0.846$). This means that Immersive Interaction Quality (Y1) is proven to fail to act as a mediating variable. Theoretically, even if a technological system boasts low latency, smooth graphics, and high object manipulation agency (technical interactivity dimensions), these physical indicators do not automatically produce changes in the learner's psychomotor abilities. An interactive learning design is merely an initial technical prerequisite that cannot stand alone to create meaningful learning.

Success of Absolute Mediation by Presence Perception Strength (H10 and H12): Conversely, indirect effect testing very convincingly accepts Hypothesis 10 ($\beta = 0.304$, $T = 4.350$, $P = 0.000$) and Hypothesis 12 ($\beta = 0.197$, $T = 2.992$, $P = 0.003$). This empirical data establishes the variable Presence Perception Strength (Y2) as a full mediator. This finding strengthens the synthesis of Krassmann et al. (2023) as well as Merino and Higuera-Trujillo (2023) that presence is a mandatory psychological bridge in the educational Virtual Reality ecosystem.

A grand metaverse environment and adequate spatial cognitive intelligence will only become meaningful for competence enhancement if both are successfully converted into a psychological presence (telepresence). When students feel integrated with their digital environment, the process of reflecting on actions, conceptualizing abstract material, and active experimentation testing (in line with Kolb's Experiential Learning Theory) will proceed naturally and deeply, ultimately yielding adaptive and ready-to-use student competence outcomes in the Society 5.0 era.

CONCLUSION

Conclusion

Based on the results of the data analysis and discussion using the Structural Equation Modeling (SEM) approach based on SmartPLS 4, this study successfully uncovers the psychological and cognitive mechanisms in the transformation of immersive technology utilization into student competence outcomes. Several main conclusions that can be drawn from this empirical testing are as follows:

1. The Metaverse-Based Learning Environment and students' internal cognitive capacity (Spatial Learning Intelligence) are proven to play crucial roles as significant antecedents in improving immersive interaction quality and strengthening students' psychological sensation of presence inside 3D virtual spaces.
2. Students' internal cognitive aspect (Spatial Learning Intelligence) has a highly massive dominant influence on the formation of immersive interaction quality. Students' mental

readiness in mapping direction and 3D visual virtual spaces becomes an absolute prerequisite so that information processing runs without causing cognitive overload.

3. Structural model testing uncovers a highly vital deconstructive finding: advanced metaverse infrastructure, high spatial intelligence, and technical interactivity do not exert a significant direct influence on experience-based competence development (Experiential Competence Development).
4. Presence Perception Strength was found to act as a full mediator in this model. The transformation from external technological readiness and students' internal cognitive capacity into real competencies (such as teamwork, leadership, and problem-solving) can only be realized if students experience an intimate psychological sensation of "being there". It is this psychological presence that drives the experiential learning cycle deeply.

Research Limitations

This study has several limitations that need to be considered when interpreting its results:

1. Data collection was conducted cross-sectionally at a single point in time, meaning it could not capture the dynamics of students' competence changes continuously (longitudinally) over prolonged use of metaverse technology.
2. This study only focuses on subjective evaluations (self-reported data) of students' perceptions through Likert scale questionnaires. It has not combined them with objective practical competence assessments directly in the field or virtual laboratories.
3. This model is limited to testing two primary mediating variables (Immersive Interaction Quality and Presence Perception Strength), thereby not yet exploring other external moderating variables such as technology anxiety or differences in students' academic discipline backgrounds.

Suggestions and Directions for Future Research

1. For Higher Education Practitioners and Developers: Instructional policymakers and lecturers are advised not to focus solely on fulfilling the luxury of metaverse technical graphic infrastructure (immersion). The primary focus must be shifted toward how to design virtual learning scenarios capable of triggering a deep psychological presence, for example, through real-time collaborative project-based assignments between avatar teams. Additionally, initial virtual space orientation training needs to be provided for students who have spatial intelligence limitations to prevent disorientation and cybersickness.
2. For Future Research: Future researchers are encouraged to use true experimental designs or mixed-methods approaches to objectively compare competence retention rates between metaverse classrooms and conventional 2D online classrooms. Future research directions could also expand the model's scope by adding lecturer characteristics or gamification elements as new moderating variables.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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