TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue II, June, 2026

IMMERSIVE LEARNING AND QUANTUM ENGAGEMENT: A FRAMEWORK FOR GEN Z IN METAVERSE CONTEXTS

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Abstract: *Educational technology keeps adding headsets and algorithms, but what actually keeps learners engaged? We introduce Quantum Engagement, a framework for sustained involvement in metaverse learning built on four forces: real-time interactivity, enacted bodily agency and presence, the emotional tone of experience, and the coherence/complexity of symbolic cues (narrative, sound, visuals, spatial design). Using a sequential mixed-methods design, we refine constructs via interviews with instructors, designers, and students, then test the model in Gen Z metaverse courses. Findings indicate that enacted presence bridges interactive design and durable engagement, symbolic richness amplifies emotional influence, and raw interactivity rarely suffices. The framework shifts attention from surface features to experiential coherence and offers guidance for curriculum, platform architecture, and strategy, with priorities for cross-cultural, longitudinal tests.*

Keywords: *Quantum Engagement; Metaverse learning; Enactive presence; Symbolic richness; Immersive interactivity.*

1. INTRODUCTION

The merging of artificial intelligence, immersive technology, and symbolic technologies is rapidly transforming the cornerstones of online education, prompting a pressing inquiry into the conceptualization and measurement of learner engagement. Investigations of Generation Z have shown a unique mental flexibility, increased emotional vulnerability, and mental plasticity that are not compatible with classical teaching structures based on the delivery of passive content and a sequential way of thinking. Our argument is informed by classical roots in motive and learning; self-determination [1], integrative educator models [2], attention/flow [3], and multimedia learning [4], but fails to explain the particularity of a saturated, immersive environment.

New managerial and educational approaches further demand human-oriented participatory perspectives. For example, Marketing 6.0 has an ethics-based, co-created, emotionally conscious innovation process, whereas the 7E model introduces experience, empathy, and balance to the front of the educational intervention process. However, these lenses are primarily descriptive and are rarely operationalized at the level of immersive learning: they do not tell us much about how learners negotiate attention, manage effort, and make sense within spatially dispersed, affect-rich, symbol-dense worlds.

We rely on enactive and embodied views and recognize the influence of affect and semiotic organization on the creation of engagement. Section 2 defines and identifies Enactive Presence (EP), Emotional Quality (EQ), and Semiotic Richness (SR). Quantum Engagement (QE) has flaws in its current models, which this study seeks to address by offering a theoretical framework. QE uptakes Immersive Interactivity (MI), embodied awareness, affective tone, and symbolic mediation into an explanation of consistent engagement that is particularly pertinent to digitally fluent learners.

The model (Fig. 1) proposes six interconnected hypotheses, which are analyzed within a mixed methods design to test direct and mediated relationships among the primary constructs.

Received: 13.04.26; **Similarities**: 16.04.26: **Reviewed**: 13.04. /13.04.26: **Accepted 16**.06.26.

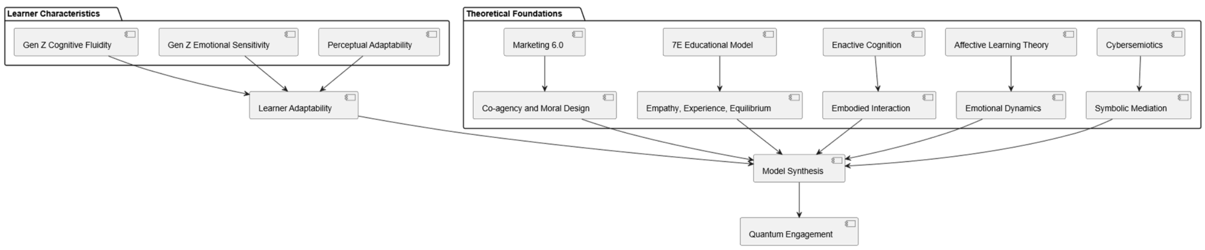

Fig. 1. Theoretical and Learner Components Synthesized into Quantum Engagement

The framework builds on the findings of embodied cognition, affective learning, and cybersemiotics to state empirically testable variables applicable to digital learning in modern contexts. The rest of the paper is structured in the following manner: Section 2 presents the literature review and conceptualization of the constructs; Section 3 presents the hypotheses; Section 4 presents the theory and construct interrelations; Section 5 presents the methodology and analysis; Section 6 presents the findings and conclusions; and Section 7 presents the contributions and future research directions.

2. LITERATURE REVIEW

The digitally augmented learning setting, revealed through the rapid adoption of immersive technologies, artificial intelligence (AI), and multimodal interfaces in education, demonstrates critical flaws in the current engagement, embodiment, cognition, and leadership frameworks. Conventional approaches to learner motivation and engagement, such as self-determination theory [4], highlight autonomy, competence, and relatedness as key variables in maintaining intrinsic motivation. These viewpoints are accompanied by broader theories of motivation in education, which emphasize the importance of self-regulation, persistence, and social-emotional learning in shaping successful learning behaviors [5,6]. Nevertheless, these strategies can offer a solid psychological foundation, but they are not sufficient to tackle the embodied, affective, and symbolic layers that define immersive learning environments.

The frameworks of marketing and educational innovation have also been interested in reconceptualizing engagement by locating it within more humanistic and participatory frameworks. The Marketing 6.0 approach makes digital transformation an ethically responsible, co-created, and emotionally focused process that harmonizes institutional practices with learners' evolving learning expectations. On the same note, the 7E model highlights empathy, experience, and balance as key aspects in participatory learning settings. Although these frameworks are essential for highlighting the significance of affect and participation, they are also descriptive and are seldom represented as quantifiable constructs in immersive education.

Conversely, studies in cognitive science have shown that immersive environments have fundamental transformative effects on learners' perceptions, actions, and meaning making. According to the theory of embodied and enactive cognition, perception, movement, and cognition are mutually constituted in real-time interactions with the environment. Of particular significance but under-researched in immersive learning systems is EP, which specifies the learner's experience of causal relations among action and environmental feedback [7-10]. Empirical research in immersive virtual reality supports the notion that embodied interaction promotes presence, motivation, and knowledge acquisition. Nevertheless, existing models rarely incorporate EP into structural explanations of engagement.

Another crucial aspect of engagement in digital learning is affective processes. EQ, which can be described as the emotional feeling of the learning experience, influences persistence and immersion in the cognitive experience. Research has also revealed that immersive environments can amplify emotional reactions, thereby affecting motivation and performance [11]. More importantly, the emotional experience does not work in isolation; it is instead mediated and enhanced by symbolic cues (narrative coherence, visual metaphor, sound design, and multimodal complexity). Understanding this figurative aspect is represented by the notion of SR, which refers to the interpretive depth and coherence of multimodal stimuli. According to semiotic attitudes, learners' meaning making does not rely solely on cognitive activities but also on embodied and symbolic encounters [12]. Although the relevance, SR has seldom been combined with affective or cognitive theories of involvement in immersive situations.

Lastly, the point of intersection between immersive learning and AI-driven learning environments necessitates reconsidering leadership and organizational processes. Educational technology studies have highlighted the transformative effects of distributed digital systems on power, agency, and co-creation. These results suggest that AI-assisted leadership practice must be reconceptualized as a decentralized, evolving process, consistent with the co-agency and collective sense-making principles. Nevertheless, the literature remains divided, and there is no common framework that relates immersive engagement, embodied cognition, semiotic mediation, and digital leadership to create a consistent model.

Overall, although the previous literature has already offered significant understanding of motivation, embodiment, affect, symbolic mediation, and institutional adaptation, an integrative framework that reflects the multidimensional nature of engagement in immersive learning is lacking. To fill this vacuum, this paper proposes QE as a theoretical framework that brings these views together. Namely, QE synthesizes the concepts of Immersive Interactivity, EP, EQ, and SR into an empirically testable model. EP is also represented as a mediator between immersive interaction and QE, and SR is a moderator in the relationship between emotional processes and long-term involvement, as shown in Figure 1. The methodology builds on previous theories by grounding engagement in embodied cognition, affective learning, and cybersemiotics, and it offers operational constructs that can be empirically validated [13]. In sum, prior work does not provide an integrative, testable account of engagement that combines interactivity, embodiment, affect, and semiotic structure.

3. HYPOTHESIS DEVELOPMENT

Building on Section 2, we translate the conceptual gaps into testable relationships among MI, EP, EQ, SR, and QE. In this research, six hypotheses are proposed to explain the roles of Immersive Interactivity, embodied awareness, emotional experience, and symbolic input in improving QE among Gen Z learners in metaverse-based courses within complex educational settings. Drawing on the theory of enactive cognition, we propose that EP is the subjective feeling of agency and of the learner's interaction through the body. Our first suggestion is that H1: MI has a positive effect on EP, based on the finding that responsive environments transform attentional orientation and motor orchestration [11]. Adding to this connection, H2: EP positively affects QE, as bodily presence has been linked to enhanced cognitive absorption and greater perseverance in immersive education [12].

This model is also highly focused on the emotional aspect. EQ, the feeling “tone” that occurs during learning, will increase involvement, especially in high-immersion conditions. Therefore, H3: EQ has a positive effect on QE, acknowledging the previous findings of the emotional intensity correlation with motivation and attention in online studies [13]. Nonetheless, such influence is most probably mediated by the layout of symbolic environments. The relationship between emotions and cognitions can be enhanced by SR, which consists of the density of visual and auditory messages or the spatiality of the experience. H4: thus, SR moderates the probability of a connection between EQ and QE, in which it is said that high SR enhances the EQ impact [14].

A direct route between interactivity and engagement complements these indirect pathways. H5: Immersive Interactivity has a favorable impact on QE, as interface quality and perceptions of control can maintain attention without emotional or embodied mediation [15].

Table 1

Hypothesized Relationships within the Quantum Engagement Framework.

Hypothesis	Theoretical Foundation	Key Constructs	Conceptual Purpose
H1: MI positively influences EP	Rooted in enactive cognition, where learning emerges through perceptual-motor coupling and active environmental engagement.	MI, EP	Establishes the perceptual-action basis of digital presence in metaverse learning environments.
H2: EP positively influences QE	Grounded in embodied engagement theory, it emphasizes the regulatory function of physical awareness in sustaining mental effort.	EP, QE	Clarifies how bodily awareness operates as a core input in learner engagement models.
H3: EQ positively influences QE	Draws from affective neuroscience and motivational psychology, highlighting the role of emotional arousal in modulating attention and persistence.	EQ, QE	Introduces emotion as a proximal driver of attentional continuity within immersive pedagogy.
H4: SR moderates the relationship between EQ and QE	Aligned with cyberelite perspectives that examine how layered symbolic systems condition the affective interpretation of multimodal content.	SR, EQ, QE	Explores the symbolic amplification of emotional resonance via dense semiotic configurations.
H5: MI positively influences QE	Anchored in embodied interface theory, it proposes that immersive interaction can elicit intrinsic motivation independently of emotional or sensory mediation.	MI, QE	Tests the residual influence of technical interactivity on engagement, beyond mediation routes.
H6: EP mediates the relationship between MI and QE	Builds on ecological models of presence, positing that sensorimotor anchoring serves as a cognitive bridge between digital input and sustained engagement.	MI, EP, QE	Explains the indirect path from interface experience to deep engagement through embodied anchoring.

Finally, H6: EP mediates the connection between MI and QE and accounts for the step-by-step way in which immersive design initially facilitates bodily presence, which, in turn, attaches to mental involvement [16]. The hypotheses (Table 1) are grounded in the theoretical aspirations of the framework and address the previous criticism by providing comprehensible, operational links among constructs based on cognitive science, engagement theory, and symbolic interaction. Section 4 explains the theoretical logic that binds these paths into a single framework. Together, these hypotheses specify the direct, mediated, and moderated relationships that the model evaluates.

4. THEORETICAL FRAMEWORK

This section integrates the constructs into a coherent model and clarifies why EP mediates and SR moderates the specified relationships. The current framework, based on the previous review, considers cognitive, affective, symbolic, and technological angles and integrates them into a single concept of engaging learners in immersive digital environments. Motivational theories, including self-determination theory and social-emotional models, inform the meanings of autonomy, persistence, and regulation in education. However, these theories are insufficient to explain how learners can maintain engagement when presented with immersive, symbolically dense, and emotionally charged experiences. The QE framework fills this gap by incorporating concepts from embodied cognition, affective neuroscience, and semiotic theory and translating them into relationships that can be empirically tested.

At the heart of this framework is EP, which is based on enactive and embodied cognition [16-19]. EP displays the learner's subjective perception of causal relationships among actions and environmental reactions and represents the anchoring of cognitive action. Existing research in the field of virtual reality establishes that embodied interaction improves presence and motivation [6-9,11,12], as a fundamental mediator that directs the effects of MI into more profound outcomes of engagement. Therefore, EP acts as the process by which sensorimotor coupling is transformed into long-term thinking and feeling.

EQ is the second pillar of the framework, and it is conceptualized as the emotional tone of the learning process. Studies have demonstrated that emotionally appealing environments contribute to persistence and attention [20-22], thus EQ is a direct cause of QE. However, EQ is not a stand-alone phenomenon but is conditioned and enhanced by the symbolic aspects of the surroundings. This results in SR being included as a modifier. SR captures the coherence, complexity, and interpretive density of multimodal cues: visual, auditory, narrative, and spatial [17,18,21]. Within this framework, it is theorized that SR conditions the relationship between EQ and QE by increasing or limiting the learner's affective resonance in response to the semiotic organization of the environment. In addition to these mediated and moderated pathways, MI is also a direct predictor of QE. This demonstrates that antecedent data indicate that interface reactivity and technical quality can sustain attention and interaction without being mediated or embodied by emotion [15]. Collectively, these mechanisms recognize that learners' engagement with immersive systems results from various convergent phenomena: direct interactivity, embodied agency, affective tone, and symbolic mediation.

All these theoretical considerations are summarized in Figure 2, which depicts the structural model of QE.

The model identifies six hypotheses where H1 asserts that MI is a predictor of EP, H2 asserts that EP is directly related to QE, H3 establishes that EQ is a direct driver of QE, H4 demonstrates that SR is a moderator between EQ and QE, H5 is a propositional one where MI has a direct relationship with QE, and H6 is a propositional one where EP is a mediator in the relationship between MI and QE. This framework offers a synthesis of concepts and an operational model that integrates disjointed understandings of motivation theory, embodied cognition, affective neuroscience, and semiotics into a single empirically testable model.

The combination of these constructs, through the framework, pushes the literature forward in two ways. Theoretically, it redefined learners' engagement as a multidimensional phenomenon that cannot be reduced to cognition, emotion, or interactivity alone. It can be used methodologically to offer clear constructs and hypothesized relationships that can be tested with structural modeling, thereby ensuring that immersion in immersive environments makes conceptual sense and is empirically supported.

5. METHODOLOGY

We adopt a sequential mixed methods design to refine construct definitions and test the theoretical model. The design aims to provide insight into the multidimensional construct of QE among Gen Z learners participating in metaverse-based educational activities. The design involves the incorporation of the initial qualitative stage of definitions refinement (the constructs) and the understanding of the relational impacts, and then the quantitative phase of testing the developed theoretical model structure.

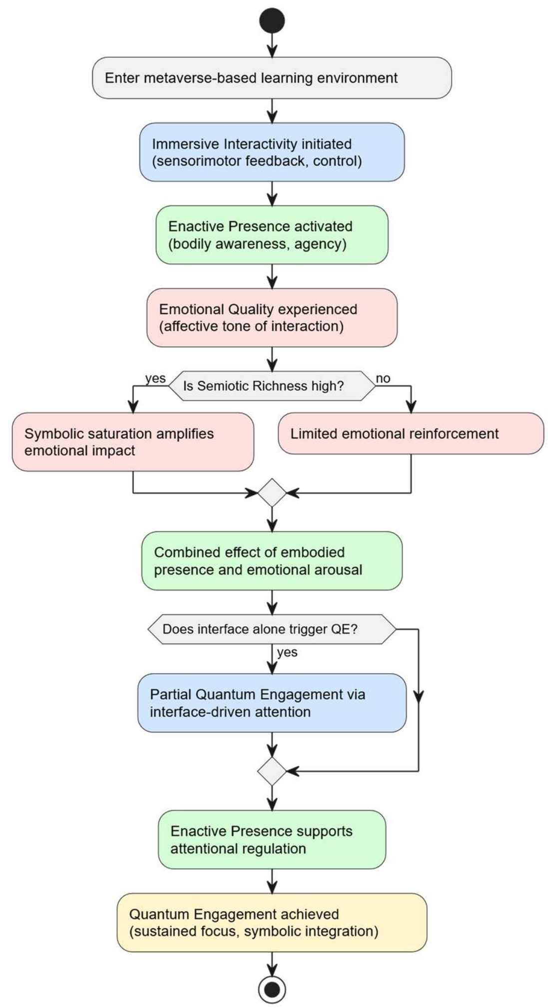

Fig. 2. Quantum Engagement Activation Flow in Metaverse-Based Learning

The combination is also intended to enhance explanatory depth and address objections previously raised regarding methodological transparency and conceptual coherence.

During the qualitative part, 12 individuals were interviewed semi-structurally: metaverse instructors, instructional designers, and student users from five European schools with established XR infrastructure. Sampling was purposeful, intended to provide variation in the immersive learning design, embodiment-based assessment, and responses to the emotional interface [23]. Interview data were collected in verbatim form and analyzed using reflexive thematic analysis with iterative coding. Stress was placed on how users referred to their body-based interaction, emotional reactions, and their sense of symbolic travel, and, based on this, the final definitions of the constructs EP, EQ, and SR were established. Inter-rater reliability has been established by coding 30% of the transcripts twice and refining the codebook through a joint review of the codes, as recommended by [3].

The following quantitative section tested the six hypotheses derived from the conceptual framework. It was decided to create a structured questionnaire based on the themes and linguistic patterns identified through the qualitative analysis, coupled with validated measurement scales from the literature on immersive learning and media psychology [4][24]. The 24 survey items covered six latent constructs and were used to survey a subset of 50 undergraduate and master's degree-supporting learners of metaverse-assisted courses of the study in business and digital innovation. After data cleaning, missing-value screening, and response bias adjustment, the sample yielded 50 valid responses.

Partial Least Squares Structural Equation Modeling (PLS SEM) was used to test the model by applying SmartPLS 4. Reflective constructs were evaluated in reliability and validity, using the elements of internal consistency (Cronbach's alpha greater than 0.80), convergence validity (average variance extracted greater than 0.50), and convergence discrimination (HTMT thresholds below 0.85) with respect to the robustness of psychometric characteristics [10]. The path coefficients, R^2 value, and predictive relevance (Q^2) were assessed using bootstrapped subsamples to determine statistical significance and model stability. Interaction terms and tests of indirect effects were used to compare moderation and mediation effects, with SR and EP included.

This approach to methodology directly addresses the concerns about conceptual ambiguity and the inadequacy of construct validation raised in the previous studies. It offers a well-organized empirical study of an inactive model of cognition that integrates symbolic interaction and affective engagement. This design achieves both contextual sensitivity and statistical rigor by triangulating qualitative context with quantitative generalizability, positioning the study within the framework of modern theories of research in educational technology [12][25]. The procedure, measures, and estimation choices enable a transparent test of the model. Section 6 presents the results and their interpretation.

6. RESULTS AND DISCUSSION

We first report on estimation quality, then evaluate each hypothesis, and finally discuss the theoretical and practical implications. The figures from the structural model supported all six hypotheses in the conceptual framework. The use of MI had a significant positive impact on EP, confirming that interactive learning environments enable more than just navigation. They assist learners in organizing motor and attentional operations, producing a greater sense of engagement. This aligns with previous research showing that embodiment through digital communication makes learners feel cognitively anchored in virtual spaces.

EP demonstrated a significant positive effect on QE, which confirmed the mediating role. The statistical power of the indirect route of MI and QE through EP outweighed that of the direct connection between the two variables. This result indicates that the relationship between engagement and the novelty of immersive systems is influenced by an internalized body-related awareness rather than a mere reaction. The gradual progression from interaction to presence, and then to engagement, shows that learners combine sensory input with a higher degree of mental involvement.

The emotional aspect also had a definite influence. The EQ positively influenced QE, consistent with the idea that emotionally rich sensations expedite motivation and cognitive reinforcement of effort [7]. In addition, SR moderated this relationship. The more difficult and meaningfully detailed the symbolic cues were, the stronger the emotional impact of the engagement became. This indicates that symbolic input amplifies the link between emotional stimulation and learning interest.

Even though MI had a direct impact on QE, this impact was not significant compared to the effects it mediated. This corroborates the argument that internalizing an interaction design does not necessarily produce an attention-persisting impact unless it is acted on by embodiment and affective resonance. In it, Gen Z learners, whom we believe are initially intrigued by interactive conditions, become engaged as long as they feel emotionally and physically immersed, and symbolic cues support meaning making.

The theoretical implications are that previous research, which focused on engagement, yielded mixed outcomes; however, the current study has shed more light on the otherwise dark subject and provided researchers with a better understanding of what engagement is. The observed findings support the view of a more holistic approach, according to which QE is a construction developed through the interplay of aspects of design, embodied perception, and the interpretation of affect. Complete immersion, body perception, emotional involvement, and SR can be combined to provide a more confident estimate of the educational experience in an XR environment.

On the practical side, metaverse-based learning institutions would be encouraged to pursue the following configurations: support agency, consistency in the narrative, and emotional truthfulness. Strategic design must include a sensory-motor component that matches physical involvement, two emotional aspects that guide what one wants to learn, and symbols to facilitate meaning construction. Educational scientists ought to offer a balance between what is new and what is familiar so that users do not feel overwhelmed yet remain intellectually and emotionally engaged.

The results provide a coherent, empirically grounded account that aligns conceptual claims with a transparent estimation strategy. The proposed model is statistically and conceptually valid and in line with current studies in cognitive science, affective learning, and semiotic interaction [6],[8]. Table 2 presents the structural links among MI, EP, EQ, and SR as meaningful predictors of quantum involvement. The model's empirical power is demonstrated in Figure 3, which shows the standardized path coefficients. These findings underscore the model's applicability to future educational paradigms. In this respect, Generation Alpha will be immersed in learning environments as natives of the metaverse, mainly communicating through avatars and artificial intelligence. Such development highlights the need for improvements in immersive, symbolically rich learning designs that address the cognitive and affective needs of emergent learner profiles. The findings support the integrated account of engagement. Section 7 summarizes the contribution and outlines future work.

Table 2

Theoretical Justification and Construct Alignment for Proposed Hypotheses

Hypothesis	Conceptual Rationale	Key Constructs	Functional Role in Framework
H1: MI → EP	Draws on sensorimotor coupling theory, where interactive feedback loops facilitate embodied presence	MI, EP	Establishes a foundational link between interface experience and bodily awareness
H2: EP → QE	Based on theories of embodied regulation, physical presence modulates sustained attention and focus.	EP, QE	Positioning embodiment as a psychological anchor for cognitive immersion
H3: EQ → QE	Informed by affective-motivational theories, emotional tone is critical to learner attentional persistence.	EQ, QE	Identifies emotional resonance as a proximal driver of engagement
H4: SR moderates EQ → QE	Inspired by cybersemiotics, symbolic complexity intensifies emotional-cognitive integration.	SR, EQ, QE	Specifies the contextual conditions under which emotion influences engagement
H5: MI → QE	Grounded in interface embodiment theory, interactivity can sustain attention independent of mediation.	MI, QE	Tests the direct effect of interactivity on engagement outside enactive/emotional pathways
H6: MI → EP → QE	Supports ecological presence models, where embodied anchoring mediates immersion to sustained effort	MI, EP, QE	Articulates an indirect path from interface experience to engagement via presence

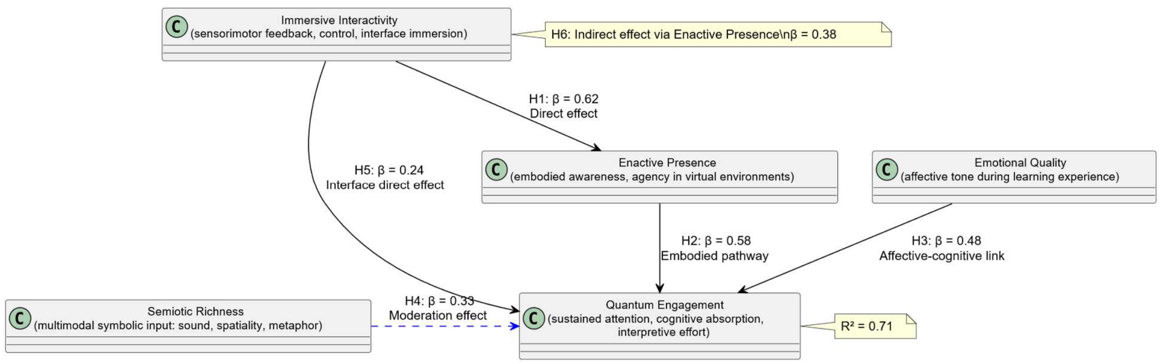

Fig. 3. Structural Path Diagram of the Quantum Engagement Model

7. CONCLUSION

The work proposes a theory-inspired, empirically grounded account of QE that would complement the experiential, cognitive, and symbolic requirements of Gen Z learners in metaverse-augmented studies. Using enactive cognition, affective engagement theory, and cybersemiotic modeling, the study offers both conceptual and statistical evidence that MI alone is insufficient to create enduring engagement. Instead, there are conjunctive results of the bodily given of the here and now, emotional response, symbolic input richness, and the interplay among them.

The results support the idea that EP mediates the relationship between immersive design and learner engagement, confirming the hypothesis that digital embodiment is a very important factor in defining attentional persistence and cognitive absorption. EQ also exerts a significant influence, primarily when supported by SR, which elicits the strongest emotional reactions through dense multimodal hints. These findings stress the need for augmented reality training environments to incorporate physical simulation, emotional design, and symbolic congruence.

Rather than the accusations of methodological inconsistency and theoretical partiality made of earlier research in the field, the present study provides an organized, mixed-methods design by establishing a connection between qualitative comprehension and quantitative extensibility. The structure addresses a gap in literature by bringing together the cognitive, affective, and symbolic pathways into a single operating model. It provides a sound basis for future empirical verification, teaching novelty, and curriculum remodeling centered on students with robust digital fluency and emotional responsiveness.

The impacts of the metaverse on institutions are both conceptual and strategic for institutions that wish to utilize metaverse platforms. It should be considered an emergency process rather than a technical result. Bodily awareness, emotional relevancy, and symbolic interpretation ought to be co-dependent principles of sustained attention that learning systems are expected to encounter. Given that the architecture of immersive education is still in development, future work should examine the effects of the model over a longer period, across cultural contexts, and in other fields.

List of abbreviations

AI: artificial intelligence, technologies, and systems that simulate human cognitive processes in digital education contexts.

AR: augmented reality, digital elements overlaid on the physical environment for educational purposes.

AVE: average variance extracted, an indicator of convergent validity for reflective constructs.

CI: confidence interval, range used to express uncertainty around statistical estimates and effects.

CR: composite reliability, an indicator of internal consistency for latent constructs.

EP: Enactive Presence, the felt sense of bodily agency and interactive control in XR environments, grounded in enactive cognition.

EQ: Emotional Quality, the emotional tone perceived during learning, including valence and intensity of affective involvement.

Gen Z: Generation Z, cohort born roughly between 1995 and 2012, digital natives with high expectations for immersive learning.

HTMT: Heterotrait Monotrait Ratio, a criterion for assessing discriminant validity in structural models; values below 0.85 indicate sufficient distinctiveness between constructs.

MI: Immersive Interactivity, quality of real-time interaction between the user and the XR environment, including sensory and symbolic feedback.
MR: mixed reality, integration of physical and virtual elements within a single interactive space.
N: sample size used in the empirical analysis.
PLS-SEM: Partial Least Squares Structural Equation Modeling, a technique for testing causal relations among latent variables, suitable for small to medium samples, mediation, and moderation.
QE: Quantum Engagement, a pattern of cognitive, emotional, social, and symbolic engagement in metaverse-based environments.
Q^2: predictive relevance, a measure of predictive performance obtained through blindfolding procedures.
R^2: coefficient of determination, proportion of variance explained for endogenous variables in the model.
SEM: structural equation modeling, a family of statistical methods for models with latent variables.
SR: Semiotic Richness, complexity, and coherence of visual, auditory, and spatial cues that support interpretation and engagement.
SRMR: standardized root mean square residual, an index of model fit in structural analysis.
VR: virtual reality, a wholly digital environment that surrounds the user and enables immersive interaction.
XR: extended reality, umbrella term that includes VR, AR, and MR.
VIF: variance inflation factor, index used to assess collinearity among indicators or predictors.

8. ACKNOWLEDGMENTS

The authors gratefully acknowledge the administrative and technical support provided by the Technical University of Cluj-Napoca during the development of this research.

9. REFERENCES

[1] Ryan, R., Deci, E., *Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being*, American Psychologist, ISSN 0003-066X, Washington, DC, 2000.

[2] Schunk, D., Pintrich, P., Meece, J., *Motivation in Education: Theory, Research, and Practice*, Pearson Higher Ed, ISBN 9780133017524, Boston, MA, 2014.

[3] Csikszentmihalyi, M., Nakamura, J., *Effortless attention in everyday life: A framework*, MIT Press, ISBN 9780262014007, Cambridge, MA, 2010.

[4] Mayer, R., *The Cambridge Handbook of Multimedia Learning*, Cambridge University Press, ISBN 9780521838733, Cambridge, 2005.

[5] Damasio, A., *Looking for Spinoza: Joy, Sorrow, and the Feeling Brain*, Houghton Mifflin Harcourt, ISBN 9780151005574, Boston, MA, 2003.

[6] Makransky, G., Mayer, R., *Benefits of immersive virtual reality in learning depend on the medium, not the message*, Computers & Education, ISSN 0360-1315, Amsterdam, 2022.

[7] Schunk, D., DiBenedetto, M., *Motivation and social-emotional learning: Theory, research, and practice,* Contemporary Educational Psychology, ISSN 0361-476X, San Diego, 2020.

[8] Makransky, G., Terkildsen, T., Mayer, R., *Adding immersive virtual reality to a science lab simulation causes more presence but less learning*, Learning and Instruction, ISSN 0959-4752, Oxford, 2019.

[9] Parong, J., Mayer, R., *Learning science in immersive virtual reality*, Journal of Educational Psychology, ISSN 0022-0663, Washington, DC, 2018.

[10] Cheng, K., Tsai, C., *Students' motivational beliefs and strategies, self-efficacy, and learning with mobile devices in STEM education,* British Journal of Educational Technology, ISSN 0007-1013, London, 2020.

[11] Radianti, J., Majchrzak, T., Fromm, J., Wohlgenannt, I., *A systematic review of immersive virtual reality applications for higher education,* Computers & Education, ISSN 0360-1315, Amsterdam, 2020.

[12] Slater, M., Sanchez-Vives, M., *Enhancing our lives with immersive virtual reality*, Frontiers in Robotics and AI, ISSN 2296-9144, Lausanne, 2016.

[13] Lombardi, L., Passalacqua, F., *Virtual reality as a tool for learning: A review on the effectiveness of VR interventions in education*, Educational Technology Research and Development, ISSN 1042-1629, New York, 2020.

[14] Webster, R., *Declarative knowledge acquisition in immersive virtual learning environments*, Interactive Learning

Environments, ISSN 1049-4820, London, 2016.

[15] Anderson, M., *Embodied cognition: A field guide*, Artificial Intelligence, ISSN 0004-3702, Amsterdam, 2003.

[16] Thompson, E., *Mind in Life: Biology, Phenomenology, and the Sciences of Mind*, Harvard University Press, ISBN 9780674025112, Cambridge, MA, 2007.

[17] Gallagher, S., *How the Body Shapes the Mind*, Oxford University Press, ISBN 9780199271943, Oxford, 2005.

[18] Gallagher, S., Lindgren, R., *Enactive metaphors: Learning through full-body engagement*, Educational Psychology Review, ISSN 1040-726X, New York, 2015.

[19] Niedenthal, P., *Embodying emotion*, Science, ISSN 0036-8075, Washington, DC, 2007.

[20] Mayer, R., *Multimedia Learning* (3rd ed.), Cambridge University Press, ISBN 9781108455801, Cambridge, 2020.

[21] Wu, B., Yu, X., Gu, X., *Effectiveness of immersive virtual reality using head-mounted displays on learning performance: A meta-analysis,* British Journal of Educational Technology, ISSN 0007-1013, London, 2020.

[22] Baceviciute, S., Mottelson, A., Terkildsen, T., Makransky, G., *Investigating representation of abstract concepts in immersive virtual reality and its effects on learning*, Virtual Reality, ISSN 1434-9957, Berlin, 2022.

[23] Domínguez, A., Saenz-de-Navarrete, J., de-Marcos, L., Fernández-Sanz, L., Pagés, C., Martínez-Herráiz, J., *Gamifying learning experiences: Practical implications and outcomes,* Computers & Education, ISSN 0360-1315, Amsterdam, 2013.

[24] Veletsianos, G., Moe, R., *The rise of educational technology as a field: A review of journals and articles, 2000–2016*, Educational Technology Research and Development, ISSN 1042-1629, New York, 2017.

[25] Jensen, L., Konradsen, F., *A review of the use of virtual reality head-mounted displays in education and training*, Education and Information Technologies, ISSN 1360-2357, New York, 2018.

Învățare imersivă și angajament cuantic: un cadru pentru generația z în contextele metaversului

Tehnologia educațională tot adaugă căști și algoritmi, dar ce îi menține de fapt pe cursanți implicați? Propunem Angajamentul Cuantic, un cadru pentru implicarea susținută în învățarea în metavers, construit pe patru forțe: interactivitatea în timp real, agenția corporală enactivă și prezența, tonalitatea emoțională a experienței și coerența/complexitatea indiciilor simbolice (narațiune, sunet, vizualuri, design spațial). Folosind un design secvențial cu metode mixte, rafinăm constructele prin interviuri cu cadre didactice, designeri și studenți, apoi testăm modelul în cursuri din metavers pentru Generația Z. Rezultatele arată că prezența enactivă face legătura între designul interactiv și angajamentul durabil, bogăția simbolică amplifică influența emoțională, iar interactivitatea în sine este rareori suficientă. Cadrul mută atenția de la caracteristicile de suprafață la coerența experiențială și oferă îndrumări pentru curriculum, arhitectura platformelor și strategie, cu priorități pentru testări transculturale și longitudinale.

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