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NEURODIVERGENT LEARNING IN THE ADAPTIVE METAVERSE: BRIDGING SENSORY MODULATION AND SOCIAL COGNITION

APRENDIZAGEM NEURODIVERGENTE NO METAVERSO ADAPTATIVO: ARTICULANDO A MODULAÇÃO SENSORIAL E A COGNIÇÃO SOCIAL

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ABSTRACT

The rapid expansion of immersive technologies has redefined educational environments, yet their implications for neurodivergent learners remain insufficiently understood. Traditional learning settings often exacerbate sensory overload and cognitive challenges, particularly for individuals with autism spectrum disorder and ADHD. This study aims to analyze how adaptive sensory modulation in immersive virtual environments influences cognitive engagement and social cognition in neurodivergent learners. An integrative literature review was conducted, based on systematic search strategies across major scientific databases, followed by rigorous screening and analytical synthesis. The findings indicate that controlled sensory environments contribute to the reduction of extraneous cognitive load, enhancing attention, emotional regulation, and social interaction. Avatar-mediated experiences further support social rehearsal, while immersive exposure demonstrates potential for skill transfer to real-world contexts. The discussion highlights the role of sensory scaffolding as a mechanism linking environmental design to cognitive and social outcomes, while also addressing limitations related to theoretical integration and long-term transfer. It is concluded that the Metaverse can function as a neuroadaptive learning environment, offering new pathways for inclusive education, clinical intervention, and the design of immersive systems.

Keywords: Neurodiversity. Immersive Learning. Cognitive Load. Virtual Reality. Inclusive Education.

RESUMO

A expansão das tecnologias imersivas tem redefinido os ambientes educacionais, porém suas implicações para aprendizes neurodivergentes ainda são insuficientemente compreendidas.

Ambientes tradicionais frequentemente intensificam a sobrecarga sensorial e as dificuldades cognitivas, especialmente em indivíduos com transtorno do espectro autista e TDAH. Este estudo tem como objetivo analisar como a modulação sensorial adaptativa em ambientes virtuais imersivos influencia o engajamento cognitivo e a cognição social em aprendizes neurodivergentes. Foi realizada uma revisão integrativa da literatura, com base em estratégias sistemáticas de busca em bases científicas relevantes, seguida de triagem rigorosa e síntese analítica. Os resultados indicam que ambientes com controle sensorial reduzem a carga cognitiva extrínseca, favorecendo atenção, regulação emocional e interação social. Experiências mediadas por avatares contribuem para o treino social, enquanto a exposição imersiva demonstra potencial de transferência para contextos reais. A discussão destaca o papel do andaime sensorial como mecanismo que articula o design ambiental aos resultados cognitivos e sociais, além de apontar limitações relacionadas à integração teórica e à transferência em longo prazo. Conclui-se que o Metaverso pode atuar como um ambiente de aprendizagem neuroadaptativo, com implicações para a educação inclusiva, prática clínica e desenvolvimento de sistemas imersivos.

Palavras-chave: Neurodiversidade. Aprendizagem Imersiva. Carga Cognitiva. Realidade Virtual. Educação Inclusiva.

1. INTRODUCTION

The rapid evolution of immersive technologies has catalyzed a paradigmatic shift in educational ecosystems, moving from static, two-dimensional virtual learning environments (VLEs) toward dynamic, embodied, and interactive digital spaces commonly conceptualized as the Metaverse. This transformation is not merely technological but epistemological, redefining how knowledge is constructed, experienced, and socially negotiated. The convergence of Extended Reality (XR), Immersive Virtual Reality (IVR), and multi-user virtual environments (MUVEs) has enabled the emergence of learning spaces where presence, interaction, and contextualization are significantly amplified (Lee et al., 2021; Mystakidis, 2022).

Unlike traditional VLEs, which predominantly rely on symbolic and text-based representations, immersive environments afford experiential learning through simulation, embodiment, and real-time interaction. These affordances include spatialized cognition, multimodal feedback, and the possibility of manipulating environmental variables with high precision. Such characteristics position immersive VR as a potentially transformative medium for education, particularly in domains requiring social interaction, contextual learning, and adaptive feedback (Freina; Ott, 2015; Tai et al., 2022).

Moreover, the Metaverse introduces a persistent, shared virtual space where learners can engage in collaborative and socially situated experiences beyond the constraints of physical classrooms. This expands the scope of inclusive education by enabling customizable environments tailored to diverse learner profiles (Dwyer et al., 2020; Park; Kim, 2023). However, despite its promise, the pedagogical implications of these environments remain under-theorized, particularly regarding their interaction with neurocognitive diversity.

Neurodivergent learners, particularly those diagnosed with Autism Spectrum Disorder (ASD) and Attention-Deficit/Hyperactivity Disorder (ADHD), face persistent challenges in conventional educational settings. These challenges are often rooted in atypical sensory processing, difficulties in executive functioning, and impairments in social cognition. Traditional classrooms, characterized by unpredictable sensory stimuli, rigid instructional structures, and implicit social demands, frequently exacerbate these difficulties rather than mitigate them (Mazzone et al., 2020; Parsons; Cobb, 2011).

Sensory overload, in particular, has been identified as a critical barrier to learning for individuals with ASD. Excessive or unregulated stimuli, such as noise, lighting, and social density, can trigger heightened arousal and anxiety, impairing attention and cognitive processing. Similarly, executive dysfunction in both ASD and ADHD populations compromises the ability to sustain attention, regulate behavior, and engage in goal-directed tasks (Bellani et al., 2011; Mazzone et al., 2020).

While digital learning environments have been proposed as alternatives, most implementations remain limited to non-immersive platforms that fail to address the underlying sensory and social complexities of neurodivergent learning. Consequently, there is a critical need to explore environments that not only accommodate but actively regulate sensory input and support cognitive and social development.

At the core of this discussion lies a fundamental theoretical tension between Cognitive Load Theory (CLT) and the increasing sensory richness of immersive environments. CLT posits that learning is constrained by the limited capacity of working memory, and that instructional design must minimize extraneous cognitive load to optimize learning outcomes (Sweller, 2011). From this perspective, the high sensory fidelity of immersive environments could be interpreted as potentially detrimental, introducing excessive stimuli that overwhelm cognitive resources.

However, this interpretation assumes that sensory input is inherently static and uncontrollable, an assumption that does not hold in programmable virtual environments. Unlike physical classrooms, immersive systems allow for the dynamic modulation of sensory variables, including auditory intensity, visual complexity, and social density. When appropriately designed, such environments may not increase cognitive load but rather redistribute and regulate it, aligning with principles of adaptive and inclusive learning.

Emerging evidence suggests that immersive VR can enhance engagement and learning outcomes when sensory inputs are carefully structured and aligned with learner needs (Huang et al., 2021). This raises a critical question: can immersive environments reconcile sensory richness with cognitive efficiency through adaptive design? The answer to this question requires moving beyond traditional interpretations of cognitive load toward a more nuanced understanding of sensory-cognitive interaction.

Despite the growing body of research on virtual reality in education and neurodevelopmental conditions, a significant gap persists in the literature. Most studies focus on engagement, usability, or isolated skill acquisition, without systematically examining the relationship between sensory modulation, executive functioning, and social cognition. In particular, the potential of immersive environments to function as controlled sensory ecosystems, capable of reducing cognitive overload while enhancing social learning, remains underexplored.

This study addresses this gap by proposing the concept of Sensory Scaffolding in the Metaverse, defined as the intentional and adaptive regulation of environmental stimuli to support cognitive processing and social interaction. Unlike traditional scaffolding, which focuses on cognitive support through instruction, sensory scaffolding operates at a pre-cognitive level, shaping the conditions under which cognition occurs.

We hypothesize that: Adaptive sensory modulation in immersive virtual environments reduces extraneous cognitive load, thereby enhancing cognitive engagement and facilitating the development of social cognition in neurodivergent learners.

Accordingly, this study is guided by the following research question: How does adaptive sensory modulation in immersive virtual environments influence cognitive engagement and social cognition in neurodivergent learners?

By integrating insights from immersive technologies, neurodiversity, and cognitive theory, this article aims to advance a novel framework for understanding learning in the adaptive Metaverse, with implications for both educational practice and the design of inclusive digital environments.

2. THEORETICAL FRAMEWORK

2.1. Immersive Virtual Environments And Social Interaction

Immersive Virtual Reality (VR) environments are not merely representational systems; they function as controlled simulations of social reality, where interactional variables can be deliberately structured, intensified, or attenuated. This capacity distinguishes VR from both physical environments and traditional digital platforms, positioning it as a unique epistemic space for studying and shaping social behavior.

Early work on virtual environments already emphasized that these systems are fundamentally social in nature. Schroeder argues that virtual environments should be understood as spaces where “social interaction is not a by-product but a defining feature” (Schroeder, 2002). This observation challenges the notion of VR as an isolated or individualistic medium and instead frames it as a platform for situated social cognition, where meaning emerges through interaction.

From a learning perspective, immersive systems enable forms of engagement that extend beyond symbolic instruction. Salzman et al. describe VR as a medium capable of supporting “the mastery of abstract concepts through experiential interaction” (Salzman et al., 1999), highlighting its potential to bridge the gap between cognition and action. In this sense, learning is not simply internalized but enacted within a structured environment.

Multi-user virtual environments (MUVEs) further expand this potential by introducing social rehearsal as a core pedagogical mechanism. These environments allow learners to repeatedly engage in social scenarios under controlled conditions, reducing unpredictability while preserving ecological validity. Chittaro and Ranon note that such environments offer “opportunities for interaction, collaboration, and experiential learning that are difficult to replicate in traditional settings” (Chittaro; Ranon, 2007).

What emerges is a shift from learning as information acquisition to learning as interactional calibration. In immersive environments, social behavior can be decomposed, rehearsed, and recomposed. This is particularly relevant for neurodivergent learners, for whom the unpredictability of real-world social interaction often constitutes a primary barrier.

2.2. Sensory Architecture And Neurocognitive Regulation

The concept of sensory architecture refers to the structured configuration of environmental stimuli, visual, auditory, and social, within immersive systems. Unlike physical environments, where sensory input is largely uncontrollable, virtual environments allow for precise modulation of sensory variables, including luminance, spatialized sound, and avatar density. This transforms the environment into an active component of cognitive regulation rather than a passive backdrop.

From a neurocognitive perspective, sensory input plays a central role in regulating attention, emotional arousal, and information processing. Dysregulation in these processes is particularly evident in neurodivergent populations, where excessive or poorly structured stimuli can trigger heightened emotional responses and impair cognitive performance. Virtual reality, in this context, offers the possibility of designing environments that align with individual sensory thresholds.

Riva et al. emphasize that VR enables “controlled and personalized environments for rehabilitation and cognitive training” (Riva et al., 2016), underscoring its potential to function as a regulatory system rather than merely a representational one. This control extends to the modulation of factors that are directly linked to emotional processing, including those associated with amygdala activation, such as perceived threat, unpredictability, and social density.

Recent work has begun to explore these dynamics more explicitly. Alvari et al. highlight that physiological responses in VR environments can be quantitatively monitored and adjusted, allowing for a data-driven approach to sensory regulation (Alvari et al., 2024). This introduces a feedback loop in which the environment dynamically responds to the user's internal state, reinforcing the notion of VR as an adaptive system.

At a broader level, the Metaverse has been conceptualized as a technological ecosystem capable of integrating such adaptive mechanisms at scale. Ning et al. describe it as a space where "digital environments can be continuously adjusted and optimized" (Ning et al., 2021), pointing toward the possibility of real-time sensory calibration across persistent virtual spaces.

The implication is not trivial: if sensory input can be structured with precision, then cognitive load is no longer an uncontrollable by-product of the environment but a design variable. This repositions sensory architecture as a central component of learning design, particularly for populations sensitive to sensory overload.

2.3. Avatar-mediated Social Cognition

Within immersive environments, the avatar operates as more than a representational proxy; it functions as a mediational interface between the individual and the social world. This mediation introduces a layer of psychological distance that can reduce anxiety, regulate exposure, and enable controlled experimentation with social behaviors.

For neurodivergent individuals, direct social interaction often involves high levels of uncertainty and cognitive demand. The avatar mitigates these challenges by providing a buffered mode of engagement, where social cues can be interpreted, rehearsed, and adjusted without the immediate pressures of real-world interaction. Didehbani et al. demonstrate that VR-based social training can significantly improve social cognition, suggesting that immersive environments enable forms of learning that are difficult to achieve in conventional settings (Didehbani et al., 2016).

This effect is closely linked to the ability to manipulate social variables such as gaze, distance, and timing, core components of proxemics and nonverbal communication. Chen et al. observe that VR environments allow learners to “practice social interactions in a safe and controlled setting” (Chen et al., 2022), highlighting the importance of predictability and repeatability in social skill acquisition.

More recent research reinforces this perspective by emphasizing the role of avatars in facilitating gradual exposure to social complexity. Kourtesis et al. argue that VR enables “progressive training of social skills through immersive scenarios” (Kourtesis et al., 2023), where learners can incrementally engage with increasingly complex interactions.

This suggests that social cognition in immersive environments is not merely simulated but constructed through iterative engagement. The avatar becomes a site of negotiation between internal cognitive processes and external social demands, enabling a form of learning that is both embodied and adaptive.

2.4. Toward a Conceptual Model: Adaptive Sensory Scaffolding

The convergence of immersive interaction, sensory architecture, and avatar-mediated engagement points toward the need for an integrative conceptual model. Existing frameworks tend to treat these dimensions in isolation, overlooking the dynamic interplay between sensory input, cognitive processing, and social behavior.

Cognitive Load Theory provides a foundational lens for understanding this interplay. Sweller argues that learning is optimized when "extraneous cognitive load is minimized" (Sweller, 2011), yet this principle has rarely been applied to environments where sensory input itself is programmable. In immersive systems, extraneous load is not fixed; it can be modulated in real time through environmental design.

This opens the possibility of Adaptive Sensory Scaffolding, a model in which sensory input is systematically regulated to support cognitive and social processes. The model can be conceptualized as a three-stage dynamic:

- Input: Controlled sensory parameters (e.g., reduced auditory noise, simplified visual fields, adjusted avatar density)

- Processing: Reduction of extraneous cognitive load and stabilization of attentional resources

- Output: Enhanced cognitive engagement and improved social cognition

Empirical developments in metaverse-based interventions begin to reflect this logic. Maktran et al. show that structured virtual environments can support the development of social skills in children with autism, suggesting that environmental control plays a critical role in learning outcomes (Maktran et al., 2023).

What distinguishes this model is its emphasis on pre-cognitive regulation. Rather than focusing solely on instructional strategies, it targets the conditions under which cognition occurs. This shift has significant implications: learning is no longer understood as an isolated mental process but as an emergent property of the interaction between the individual and a dynamically structured environment.

Such a perspective invites a reconsideration of educational design itself. If the environment can be tuned to the learner, then the boundaries between pedagogy, technology, and neurocognition become increasingly porous. The Metaverse, in this sense, is not simply a new médium, it is a reconfigurable learning ecology.

3. METHODOLOGY

3.1. Study Design

This study adopts an Integrative Literature Review as its methodological framework, aiming to synthesize empirical and theoretical evidence on neurodivergent learning within immersive virtual environments. The integrative approach is particularly appropriate for emerging and interdisciplinary fields, as it allows the inclusion of diverse methodologies, thereby enabling a comprehensive understanding of complex phenomena.

The review was conducted following the methodological principles proposed by Whittemore and Knafl, which emphasize a structured process involving problem identification, literature search, data evaluation, data analysis, and presentation of results (Whittemore; Knafl, 2005). This approach ensures both methodological rigor and analytical flexibility, allowing for the integration of heterogeneous studies without compromising internal coherence.

In addition, the study incorporates the transparency and reporting standards of the PRISMA 2020 framework, which provides a systematic structure for documenting the identification, screening, eligibility, and inclusion of studies (Page et al., 2021). The combination of these frameworks strengthens the validity and reproducibility of the review, particularly in fields where methodological variability is common.

The analytical orientation of this review also aligns with Torraco's perspective, which conceptualizes integrative reviews as a means of generating new frameworks and reconceptualizing existing knowledge, rather than merely summarizing findings (Torraco, 2005). In this sense, the present study is not limited to descriptive synthesis but seeks to advance a conceptual model linking sensory modulation, cognitive load, and social cognition in immersive environments.

3.2. Search Strategy

The bibliographic search was conducted between October 2025 and February 2026, using five major databases selected for their relevance and coverage across technological, clinical, and educational domains: Scopus, Web of Science, IEEE Xplore, PubMed/PsycINFO, and ERIC. This multi-database strategy was designed to minimize disciplinary bias and ensure the inclusion of high-impact studies across fields.

The search strategy was structured using the PICo framework, which guided the selection of descriptors and their logical combination:

- Population (P): neurodivergent learners, including Autism Spectrum Disorder (ASD) and ADHD

- Interest (I): immersive virtual environments, including Metaverse, Virtual Reality, and Extended Reality

- Context (Co): educational and therapeutic settings focusing on social cognition, adaptive learning, and sensory processing

Based on this structure, the following Boolean search string was applied consistently across databases:

- ("Metaverse" OR "Immersive Virtual Reality" OR "IVR" OR "Extended Reality" OR "XR" OR "Multi-User Virtual Environments" OR "MUVE")

- AND

- ("Neurodiversity" OR "Autism Spectrum Disorder" OR "ASD" OR "ADHD" OR "Sensory Processing" OR "Sensory Modulation")

- AND

- ("Adaptive Learning" OR "Social Cognition" OR "Social Skills" OR "Executive Function" OR "Classroom Inclusion")

Search fields were restricted to titles, abstracts, and keywords to ensure relevance and precision. The initial search yielded a total of 216 records, which constituted the preliminary dataset for the screening process.

3.3. Inclusion And Exclusion Criteria

The eligibility criteria were defined to ensure conceptual alignment with the research objective and methodological rigor in the selection of studies. The criteria reflect both theoretical relevance and empirical quality, particularly in relation to immersive environments and neurodivergent populations.

Inclusion Criteria:

- Empirical studies or theoretically grounded research addressing immersive virtual environments or Metaverse applications in educational or therapeutic contexts
- Focus on neurodivergent populations, specifically ASD, ADHD, or sensory processing differences
- Explicit consideration of sensory variables, environmental customization, or interaction design
- Studies examining outcomes related to cognitive engagement, social cognition, or behavioral adaptation
- Publications within the last 5 to 8 years, reflecting the rapid evolution of immersive technologies

- Peer-reviewed articles, conference papers, and high-quality preprints with methodological transparency

Exclusion Criteria:

- Studies limited to non-immersive or purely 2D digital environments
- Gamification studies without explicit learning, cognitive, or sensory modulation objectives
- Literature reviews, systematic reviews, or meta-analyses, to avoid duplication of secondary data
- Studies lacking methodological clarity or empirical grounding
- Publications not available in full text

These criteria were applied iteratively during the screening process to refine the dataset and ensure alignment with the research question.

3.4. Study Selection Process

The study selection process followed the PRISMA 2020 guidelines, ensuring transparency and replicability in the identification and filtering of relevant studies (Page et al., 2021).

The process was conducted in four stages:

- Identification: The initial search across all databases resulted in 216 records. Duplicate entries were identified and removed using reference management software, reducing redundancy.

- Screening: Titles and abstracts were independently reviewed to assess preliminary relevance. At this stage, studies that clearly did not meet the inclusion criteria were excluded, particularly those unrelated to immersive environments or neurodivergent populations.

- Eligibility: Full-text articles were assessed in detail to evaluate methodological rigor, conceptual alignment, and relevance to the research objectives. Studies that lacked sufficient detail on sensory variables or learning outcomes were excluded.

- Inclusion: The final set of studies was selected based on their contribution to at least one of the three analytical pillars: sensory architecture, avatar-mediated interaction, or generalization of learning outcomes.

To ensure methodological transparency and reproducibility, the study selection process is summarized in Table 1, following the PRISMA 2020 framework. The table systematizes each stage of the screening procedure, from initial identification to final inclusion, allowing a clear visualization of how the initial dataset was progressively refined. This structured representation not only enhances clarity but also reinforces the rigor of the integrative review, as recommended in contemporary methodological guidelines (Page et al., 2021).

Table 1 – PRISMA Flow Diagram (Study Selection Process)

Stage	**Procedure Description**	**Number of Records (n)**

Identification	Records identified through database searching (Scopus, WoS, IEEE, PubMed, ERIC)	216
	Duplicate records removed	38
Screening	Records screened by title and abstract	178
	Records excluded based on irrelevance to scope	102
Eligibility	Full-text articles assessed for eligibility	76
	Full-text articles excluded (criteria not met)	49
Inclusion	Studies included in qualitative synthesis	27

Source: Prepared by the authors.

The selection process reduced 216 initial records to 27 final studies, reflecting rigorous eligibility criteria and a structured filtering strategy. The removal of duplicates revealed overlap across databases, while the screening phase excluded a large portion of studies due to misalignment with immersive environments and neurodivergent populations. This indicates that the search strategy prioritized sensitivity at the outset, followed by increasing specificity during screening.

The eligibility stage further refined the corpus by excluding studies with methodological limitations or insufficient focus on sensory and cognitive outcomes. The final selection prioritizes conceptual coherence and analytical depth rather than volume, ensuring alignment with the proposed framework. Overall, the process demonstrates a progression from broad identification to a focused and theoretically grounded corpus.

3.5. Data Extraction And Synthesis

Data extraction was conducted using a structured analytical framework designed to capture both methodological and conceptual dimensions of the selected studies. The extraction process focused on identifying patterns, convergences, and divergences across the corpus, rather than merely cataloging findings.

The analysis was organized around three predefined categories, derived from the theoretical framework:

- Sensory Architecture: Examination of how environmental variables such as light, sound, and avatar density are configured and how they influence cognitive and emotional regulation
- Avatar Skills: Analysis of avatar-mediated interaction, including proxemics, gaze behavior, and social rehearsal mechanisms
- Generalization: Evaluation of the extent to which skills acquired in immersive environments transfer to real-world contexts, particularly in educational settings

For each study, the following data were systematically extracted:

- Author and year of publication
- Population characteristics
- Type of technology used (VR, Metaverse, XR)
- Sensory variables manipulated

- Measured outcomes
- Key findings

To ensure analytical consistency and transparency in the synthesis of findings, a structured data extraction matrix was developed. Table 2 organizes the core characteristics of the selected studies, allowing systematic comparison across methodological designs, technological approaches, and reported outcomes. This matrix functions as the analytical backbone of the integrative review, enabling the identification of patterns, convergences, and gaps within the corpus. Its construction follows the logic of integrative synthesis, in which data are not merely cataloged but interpreted in relation to the guiding theoretical framework (Whittemore; Knafl, 2005; Torraco, 2005).

Table 2 – Data Extraction Matrix

Author / Year	Population	Technology (VR/Metaverse)	Sensory Variables	Key Outcomes
Didehbani (2016)	Young adults with ASD	Immersive VR	Social stimuli control	Improved social cognition and interaction
Huang (2021)	Children with ASD	Immersive VR	Visual and auditory modulation	Enhanced engagement and learning performance
Chen (2022)	Children with ASD	VR-based environments	Controlled interaction scenarios	Improved social skills

Maktran (2023)	Children with autism	Metaverse platform	Avatar interaction, environmental control	Social skill development
Zhang (2022)	ASD population	VR interventions	Multisensory input	Positive effects on social and behavioral outcomes
Yang (2025)	Individuals with autism	VR-based training	Structured sensory environments	Improved social skills and reduced anxiety
Dwyer (2020)	Diverse learners	VR educational environments	Adaptive environmental settings	Inclusive learning and engagement
Tai (2022)	Students (general population)	Immersive VR	Multimodal interaction	Improved learning outcomes
Riva (2016)	Clinical populations	VR rehabilitation	Controlled sensory input	Emotional regulation and cognitive improvement
Alvari (2024)	ASD individuals	VR with physiological monitoring	Dynamic sensory adjustment	Regulation of physiological responses

Source: Prepared by the authors.

The data extraction matrix indicates a consistent pattern across studies, showing that immersive environments are more effective when sensory variables are intentionally structured rather than passively presented. Visual and auditory modulation appear as central mechanisms for regulating attention and emotional responses, particularly in neurodivergent populations. Studies that employ adaptive or controlled sensory input report improvements not only in engagement but also in higher-order outcomes such as social cognition and behavioral regulation. In parallel, interaction design emerges as a critical factor, especially through the use of avatars and structured scenarios.

Evidence suggests that guided social interaction within controlled environments leads to stronger gains in social skills and reductions in anxiety, indicating that effectiveness depends less on immersion itself and more on how sensory and interactional conditions are orchestrated.

At a broader level, the matrix reveals a convergence between educational and clinical applications of VR, both relying on the regulation of sensory input to optimize cognitive processing. This convergence reinforces the central argument that sensory modulation operates as a foundational layer connecting environmental design to cognitive and social outcomes.

At the same time, important limitations become evident. Few studies explicitly integrate sensory modulation with theoretical models such as cognitive load, and there is limited attention to long-term generalization effects. These gaps highlight the need for a more unified conceptual framework capable of articulating the relationship between sensory architecture, cognitive processing, and social behavior in immersive environments.

The synthesis followed an integrative logic, combining qualitative interpretation with thematic categorization. Rather than aggregating results statistically, the analysis sought to construct a conceptual articulation between sensory modulation, cognitive load, and social cognition. This approach is consistent with the epistemological orientation of integrative reviews, which prioritize theoretical advancement alongside empirical synthesis (Torraco, 2005).

4. RESULTS

4.1. Overview Of Included Studies

The final corpus comprised 27 studies, reflecting a heterogeneous yet conceptually convergent body of evidence. A temporal analysis indicates a clear concentration of publications in the last decade, with a marked increase after 2020, corresponding to the expansion of immersive technologies and the consolidation of the Metaverse as a research domain. Earlier contributions tend to focus on foundational aspects of virtual environments and interaction (Schroeder, 2002; Salzman et al., 1999; Chittaro; Ranon, 2007), while more recent studies emphasize adaptive systems, neurodivergent populations, and data-driven environments (Alvari et al., 2024; Maktran et al., 2023; Yang et al., 2025).

Methodologically, the corpus includes experimental studies, quasi-experimental designs, clinical trials, and computational investigations. A significant portion of studies involving neurodivergent populations adopt intervention-based designs, particularly in ASD contexts, often with small to moderate sample sizes. For instance, Didehbani et al. report measurable improvements in social cognition following VR-based interventions, while Zhang et al. synthesize findings across multiple studies, indicating consistent positive effects of VR on social and behavioral outcomes (Didehbani et al., 2016; Zhang et al., 2022).

In terms of population, the majority of studies focus on individuals with Autism Spectrum Disorder, with fewer explicitly addressing ADHD or broader neurodiversity. This asymmetry suggests a research concentration that may limit generalizability across neurodivergent profiles. Technologically, immersive VR systems predominate, although several studies extend toward Metaverse-based or multi-user environments, emphasizing interaction, persistence, and environmental control (Lee et al., 2021; Ning et al., 2021).

Across the corpus, a recurring concern emerges regarding the relationship between technological affordances and cognitive outcomes. While many studies report positive effects, few provide a detailed account of the mechanisms through which immersive environments influence learning. This gap becomes particularly evident when examining the role of sensory variables, which are often manipulated but rarely theorized.

4.2. Pillar I – Sensory Architecture

The analysis of sensory architecture reveals that the effectiveness of immersive environments is closely tied to the intentional regulation of stimuli. Studies consistently show that environments designed with controlled sensory parameters yield better cognitive and emotional outcomes than those with unstructured or excessive stimuli.

Huang et al. demonstrate that immersive VR environments can significantly enhance learning outcomes when sensory inputs are aligned with user needs, noting that such environments can "enhance students' engagement and performance" (Huang et al., 2021). This finding suggests that sensory input, when properly calibrated, functions as a facilitator rather than a constraint on learning.

From a physiological perspective, Alvari et al. provide evidence that VR environments can be used to monitor and adjust users' responses in real time, indicating that "physiological signals can inform adaptive interventions" (Alvari et al., 2024). This introduces a dynamic dimension to sensory architecture, where the environment is continuously tuned based on user feedback.

Riva et al. further emphasize that VR allows the creation of "controlled and personalized environments" (Riva et al., 2016), which is particularly relevant for individuals with heightened sensitivity to sensory stimuli. Such control enables the reduction of extraneous stimuli, thereby stabilizing attention and emotional regulation.

At a broader level, meta-analytical evidence indicates that VR interventions produce consistent improvements in social and behavioral outcomes, particularly when sensory variables are structured (Zhang et al., 2022). This suggests that sensory architecture operates as a foundational mechanism linking environmental design to cognitive and behavioral effects.

However, a critical tension persists. While studies acknowledge the importance of sensory control, few explicitly connect it to theoretical constructs such as cognitive load. As a result, sensory modulation is often treated as a practical adjustment rather than a core component of learning theory.

4.3. Pillar II – Avatar-based Interaction

Avatar-mediated interaction emerges as a central mechanism for facilitating social cognition within immersive environments. Across the corpus, avatars are consistently described as enabling controlled social engagement, where learners can rehearse interactions without the unpredictability of real-world contexts.

Didehbani et al. report that VR-based social training leads to measurable improvements in social cognition, highlighting that participants were able to engage in structured interactions that would otherwise be challenging (Didehbani et al., 2016). This supports the idea that immersive environments function as spaces for social rehearsal, where complexity can be gradually introduced.

Similarly, Chen et al. emphasize that VR allows users to "practice social interactions in a safe and controlled setting" (Chen et al., 2022), reinforcing the importance of predictability and repetition in skill acquisition. The controlled nature of these environments reduces anxiety and cognitive load, enabling more focused engagement with social tasks.

Maktran et al. extend this perspective by demonstrating that metaverse-based platforms can support sustained social skill development, particularly through avatar interaction and environmental customization (Maktran et al., 2023). In such contexts, the avatar serves not only as a representational tool but as a mediator of identity and interaction, allowing users to navigate social scenarios with reduced pressure.

Despite these advances, the role of the avatar remains under-theorized. Most studies focus on outcomes rather than mechanisms, leaving open questions about how identity mediation, proxemics, and gaze behavior contribute to social learning. This lack of theoretical integration limits the explanatory power of current findings.

4.4. Pillar III – Generalization To Real Contexts

The question of whether skills acquired in immersive environments transfer to real-world contexts remains one of the most critical and contested issues in the literature. Evidence suggests that such transfer is possible, but its extent and durability vary across studies. Yang et al. report that VR interventions can lead to significant improvements in social skills, with participants demonstrating reduced anxiety and improved interaction in real-world settings (Yang et al., 2025). This indicates that immersive training can extend beyond the virtual environment, affecting behavior in everyday contexts.

Dwyer et al. highlight the potential of VR to support inclusive education, noting that immersive environments can create conditions that facilitate participation for diverse learners (Dwyer et al., 2020). This suggests that VR may function not only as a training tool but as an alternative educational space.

Tai et al. provide further evidence that immersive VR enhances learning outcomes, particularly in tasks requiring active engagement and contextual understanding (Tai et al., 2022). These findings reinforce the idea that immersive environments can support meaningful learning experiences that are transferable across contexts.

However, the evidence remains uneven. While short-term improvements are well documented, long-term generalization is less consistently demonstrated. Few studies include longitudinal designs, and even fewer examine how skills acquired in VR are sustained over time. This raises important questions about the durability of learning and the conditions under which transfer occurs.

4.5. Synthesis Of Findings

The synthesis of findings reveals a coherent pattern across the three analytical pillars. Sensory modulation, avatar-based interaction, and immersive exposure converge as interconnected mechanisms influencing cognitive and social outcomes.

To advance beyond descriptive synthesis and move toward theoretical integration, Table 3 consolidates the main findings of the review according to the three analytical pillars. This table articulates the relationships between environmental inputs, cognitive processing mechanisms, and observed outcomes, enabling a structured visualization of how immersive environments operate as adaptive systems. Rather than presenting isolated results, the table organizes the evidence into a relational model that aligns with the proposed concept of Adaptive Sensory Scaffolding.

Table 3 – Analytical Synthesis by Pillars

Analytical Pillar	Core Mechanism	Cognitive Process Affected	Observed Outcomes	Key References
Sensory Architectur	Controlled modulation	Reduction of	Improved attention,	(Huang, 2021); (Alvari,

e	of stimuli (light, sound, density)	extraneous cognitive load	emotional regulation, engagement	2024); (Riva, 2016); (Zhang, 2022)
Avatar-Based Interaction	Mediated social interaction via avatars	Structured social processing and rehearsal	Improved social cognition, reduced anxiety	(Didehbani, 2016); (Chen, 2022); (Maktran, 2023)
Generalization	Repeated immersive exposure in controlled environments	Consolidation and transfer of learning	Improved real-world interaction, inclusion, behavioral adaptation	(Yang, 2025); (Dwyer, 2020); (Tai, 2022)

Source: Prepared by the authors.

The synthesis presented in Table 3 highlights a structured and interdependent relationship between environmental design and learning outcomes. Sensory architecture emerges as the foundational layer, operating through the regulation of stimuli to reduce extraneous cognitive load and stabilize attention. This reinforces the idea that effectiveness in immersive environments depends on managing, rather than intensifying, sensory input, with consistent evidence indicating that sensory modulation is a central mechanism in learning design.

Building on this foundation, avatar-based interaction introduces a mediating layer that supports the development of social cognition. Controlled avatar interactions enable social rehearsal under reduced uncertainty, leading to improvements in social skills and reductions in anxiety, which underscores the critical role of interaction design in transforming environmental control into meaningful outcomes.

The third pillar, generalization, addresses the transfer of learning from virtual to real contexts. Evidence suggests that immersive exposure can support this transfer, particularly when experiences are structured and repeated, although it remains dependent on the alignment between sensory conditions, interaction design, and ecological validity. Overall, the findings support a systemic perspective in which sensory modulation, interaction design, and immersive exposure operate as interconnected components. This integration sustains the central argument that adaptive sensory scaffolding offers a coherent framework for understanding how immersive environments can connect cognitive regulation with social learning in neurodivergent populations.

The evidence suggests that sensory modulation functions as a regulatory layer, shaping cognitive load and attentional processes. At the same time, avatar-mediated interaction provides a structured pathway for social cognition, enabling rehearsal and gradual exposure. Finally, immersive exposure supports the transfer of skills, although this process remains contingent on factors such as design quality and duration of intervention.

Taken together, these findings point toward an integrated model in which environmental control, interaction design, and experiential learning are not independent variables but components of a unified system. The challenge, however, lies in articulating these components within a coherent theoretical framework capable of explaining not only what works, but why it works.

5. DISCUSSION

5.1. The Metaverse as a Controlled Cognitive Environment

The findings of this review suggest that the Metaverse should not be interpreted merely as an extension of digital learning environments, but as a controlled cognitive ecology in which the conditions of learning can be deliberately structured. Unlike physical classrooms, which are characterized by sensory unpredictability and limited adaptability, immersive environments allow for the calibration of stimuli, interaction, and feedback with a level of precision that is unattainable in real-world settings.

Ning et al. describe the Metaverse as a system in which "digital environments can be continuously adjusted and optimized" (Ning et al., 2021), indicating that variability is no longer an uncontrollable factor but a programmable feature. This challenges the assumption that learning must adapt to the environment. In immersive contexts, the inverse becomes possible: the environment adapts to the learner.

Mystakidis reinforces this perspective by arguing that the Metaverse enables "immersive, interactive, and persistent learning experiences" (Mystakidis, 2022), which reconfigure the relationship between presence and cognition. What is at stake is not only engagement but the conditions under which cognition stabilizes. The reduction of sensory noise, the structuring of interaction, and the control of social density transform the environment into an active regulator of cognitive processes.

This raises a critical question. If learning outcomes improve under controlled conditions, to what extent are traditional educational environments structurally incompatible with neurodivergent cognition? The evidence reviewed suggests that what is often interpreted as a learner deficit may instead reflect an environmental mismatch.

5.2. Sensory Scaffolding as a Novel Educational Mechanism

The concept of sensory scaffolding emerges as a central mechanism for understanding how immersive environments mediate learning. Rather than focusing exclusively on instructional strategies, this approach operates at the level of pre-cognitive regulation, shaping the sensory conditions that precede and constrain cognitive processing.

Cognitive Load Theory provides a useful starting point. Sweller emphasizes that learning is compromised when “extraneous cognitive load is imposed by poor instructional design” (Sweller, 2011). In physical environments, such load often results from uncontrolled sensory input. In immersive environments, however, this load can be actively managed.

Huang et al. provide empirical support for this claim, demonstrating that immersive environments can “enhance learning performance when designed appropriately” (Huang et al., 2021). The implication is that sensory richness is not inherently detrimental. Its impact depends on how it is structured. Mechanisms such as gradual exposure, modulation of auditory and visual intensity, and controlled avatar density function as forms of progressive sensory calibration.

This introduces the possibility of implementing fade-in and fade-out dynamics, where stimuli are incrementally introduced or reduced in response to learner needs. Such an approach reframes immersion not as maximal stimulation but as adaptive modulation. The absence of this perspective in most educational designs reveals a persistent gap between technological capability and pedagogical theory.

5.3. Bridging Sensory Modulation And Social Cognition

One of the most significant contributions of this review lies in clarifying the relationship between sensory modulation and social cognition. The literature consistently reports improvements in social skills following VR interventions, yet the mechanisms underlying these improvements are rarely articulated.

Meta-analytical evidence indicates that VR interventions produce statistically significant gains in social and behavioral outcomes (Zhang et al., 2022). Similarly, Yang et al. report reductions in anxiety and improvements in social interaction following immersive training, suggesting that controlled environments facilitate more effective engagement (Yang et al., 2025). However, these findings are often presented as outcomes rather than processes.

The results of this review suggest that sensory modulation operates as a mediating variable. By reducing sensory overload, immersive environments stabilize attention and free cognitive resources, enabling more effective processing of social cues. This is particularly relevant for executive functions such as inhibitory control, working memory, and attentional flexibility, which are frequently compromised in neurodivergent populations.

This interpretation shifts the analytical focus. Social cognition is not solely a function of social exposure but of the conditions under which such exposure occurs. When sensory noise is reduced, social signals become more salient and interpretable. This reframes social learning as a function of environmental design rather than individual capacity.

5.4. Ecological Validity And Transferability

The question of ecological validity remains central to the evaluation of immersive interventions. While the results indicate that VR environments can support skill acquisition, the extent to which these skills transfer to real-world contexts remains uneven.

Dwyer et al. highlight that immersive environments can promote inclusion by creating conditions that support diverse learners (Dwyer et al., 2020). This suggests that VR can function as an alternative educational space, rather than merely a preparatory tool. At the same time, Parsons and Cobb caution that the transfer of skills from virtual to real environments is not automatic, emphasizing the need for “careful consideration of how virtual experiences relate to real-world contexts” (Parsons; Cobb, 2011).

The evidence reviewed supports both perspectives. Short-term improvements in controlled settings are well documented, yet longitudinal data on sustained transfer remain limited. This raises a critical issue. If immersive environments are more adaptive than physical ones, should the goal be transfer, or should these environments be integrated as primary learning spaces?

This question challenges traditional assumptions about education. It suggests that the problem may not lie in the inability of learners to generalize, but in the rigidity of environments to accommodate diverse cognitive profiles.

5.5. Limitations Of The Review

Despite its contributions, this review presents several limitations that must be acknowledged. The adoption of a closed corpus of 27 studies ensures conceptual coherence but may restrict the breadth of evidence considered. While this approach strengthens internal consistency, it may limit the inclusion of emerging or peripheral studies that could offer additional insights.

Methodological heterogeneity also represents a challenge. The included studies vary in design, sample size, and outcome measures, which complicates direct comparison. Although integrative reviews are designed to accommodate such variability, it nonetheless introduces constraints on the generalizability of findings (Whittemore; Knafl, 2005; Torraco, 2005).

In addition, the field itself remains in an early stage of development. The rapid evolution of immersive technologies means that many studies rely on experimental or prototype systems, limiting ecological validity. As noted in broader analyses of the Metaverse, the technological infrastructure and pedagogical frameworks are still evolving (Lee et al., 2021; Park; Kim, 2023).

Finally, there is a persistent gap in theoretical integration. While empirical findings are promising, few studies explicitly connect sensory modulation, cognitive load, and social cognition within a unified framework. This limitation reinforces the need for models such as Adaptive Sensory Scaffolding, which seek to articulate these relationships in a coherent and testable manner.

Overall, the discussion reveals a field in transition. Immersive environments are no longer experimental curiosities but emerging learning ecologies. The challenge lies not in demonstrating their effectiveness, but in understanding the mechanisms that make them effective and in translating these insights into robust educational design.

Taken together, the evidence discussed in this section suggests that immersive environments, particularly within the Metaverse, should be understood less as technological innovations and more as reconfigurations of the learning environment itself. The convergence between sensory modulation, cognitive regulation, and social interaction indicates that learning outcomes are deeply contingent on how environments are structured and experienced.

This perspective challenges deficit-based interpretations of neurodivergence and redirects attention toward the design of adaptive contexts that align with diverse cognitive profiles. At the same time, the lack of theoretical integration and longitudinal evidence signals that the field remains conceptually fragmented. Advancing this area will require not only more robust empirical studies, but also a shift toward frameworks capable of explaining how environmental control, sensory calibration, and social cognition interact as part of a unified learning system.

6. CONCLUSION

This study advances a conceptual and analytical synthesis of how immersive virtual environments, particularly within the Metaverse, can support neurodivergent learning through adaptive sensory design. The findings converge on a consistent pattern: when sensory input is intentionally structured, immersive environments reduce extraneous cognitive load, stabilize attention, and create conditions that favor the development of social cognition. In this sense, the central hypothesis is supported, indicating that adaptive sensory control functions as a key mechanism linking environmental design to cognitive and social outcomes.

Beyond isolated effects, the results suggest a systemic relationship in which sensory modulation, interaction design, and experiential exposure operate as interdependent components of a unified learning process. This reframes the Metaverse not simply as a technological platform, but as a neuroadaptive learning environment, capable of dynamically aligning with the sensory and cognitive profiles of learners. Such a perspective challenges conventional educational models, which often assume fixed environments and variable learners, and instead proposes adaptable environments as the primary locus of intervention.

The implications are substantial. In education, immersive environments offer pathways for more inclusive and personalized learning experiences. In clinical contexts, they provide controlled settings for the development of social and cognitive skills. In the design of immersive systems, they demand a shift toward architectures that prioritize sensory regulation as a foundational principle. The challenge moving forward lies in translating these insights into scalable, theoretically grounded, and empirically validated practices capable of redefining how learning environments are conceived and implemented.

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