

Review

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Review

The Impact and Integration of Biofeedback and Game-Based Learning in Special Education: A Global Perspective on Early Childhood Intervention

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Abstract

This study presents a comprehensive comparative thematic literature review examining the role of biofeedback and game-based learning (GBL) technologies in early childhood special education, focusing on children aged 4 to 10 diagnosed with special educational needs (SEN), including attention-deficit/hyperactivity disorder (ADHD), autism spectrum disorder (ASD), developmental coordination disorder (DCD), and specific learning disabilities. As the demand for inclusive, adaptive, and developmentally appropriate interventions increases globally, biofeedback and GBL have emerged as promising approaches that combine interactivity, personalization, and real-time feedback to foster cognitive, emotional, and behavioral development. Drawing on 16 peer-reviewed empirical studies published between 2010 and 2024, this review identifies and synthesizes outcomes across five thematic domains: (1) enhancement of cognitive and executive functions, (2) emotional and behavioral regulation, (3) learner engagement and motivation, (4) classroom integration and pedagogical alignment, and (5) systemic barriers and ethical considerations. The results indicate that both modalities—particularly when combined in hybrid formats—are effective in improving working memory, attentional control, anxiety reduction, self-regulation, and learner persistence. Interventions utilizing wearable biosensors or neurofeedback devices enhanced emotional awareness and behavioral self-regulation, while GBL platforms with adaptive difficulty and customizable features increased intrinsic motivation and task engagement. However, the integration of these technologies in educational practice is frequently limited by practical and systemic barriers, including high implementation costs, lack of teacher training, inadequate technological infrastructure, sensory overstimulation risks, and the absence of culturally and linguistically localized content. The review underscores the importance of aligning digital interventions with individualized education plans (IEPs) and providing continuous professional development for educators. It also highlights the need for robust ethical frameworks to regulate the use of biometric data and ensure informed consent, particularly in school settings. Ultimately, biofeedback and GBL tools represent a shift toward more inclusive, embodied, and responsive models of learning that support neurodiverse students not only in achieving academic goals but also in developing lifelong self-regulation and emotional resilience skills. For these tools to fulfill their transformative potential, coordinated efforts are required among educators, policymakers, developers, and researchers to design, implement, and evaluate interventions that are not only innovative but also equitable, scalable, and ethically sound.

Keywords: biofeedback; game-based learning; special education; ADHD; autism; inclusive technology; early childhood; educational innovation

Introduction

In the last two decades, the global landscape of special education has undergone a significant transformation, driven in part by increased societal awareness of neurodiversity, shifts in policy emphasizing inclusion, and rapid advancements in educational technology (UNESCO, 2021; Papadakis et al., 2017). This transformation has led to a reconceptualization of how educators, policymakers, and researchers understand and respond to the learning needs of children with special educational needs (SEN). Among the many innovations emerging from this evolution, biofeedback and game-based learning (GBL) stand out as particularly promising tools for facilitating engagement, regulation, and cognitive growth among neurodiverse children (Arns et al., 2009; Scholten et al., 2016).

Biofeedback refers to a family of interventions grounded in psychophysiology that enable individuals to gain awareness and voluntary control over certain autonomic functions—such as heart rate variability (HRV), electrodermal activity (EDA), and respiration—through real-time digital feedback (Yucha & Montgomery, 2008; Hammond, 2011). In children with conditions such as ADHD and ASD, dysregulation of these functions is common and often correlated with emotional and behavioral challenges (Thompson & Thompson, 2003; Drexler et al., 2019). Biofeedback technologies, often wearable and non-invasive, provide a means of translating abstract internal states into accessible, visual formats, enabling children to learn strategies for emotional self-regulation, improved attention, and impulse control (Parker & Albrecht, 2020).

A notable subtype of biofeedback is neurofeedback, which targets brainwave activity, particularly in regions associated with executive functioning. Neurofeedback has been shown to yield improvements in attention span, working memory, and behavioral inhibition in children diagnosed with ADHD (Arns et al., 2009; Prins et al., 2011; Kalkman et al., 2020). These outcomes are supported by neuroimaging studies indicating increased frontal lobe activity following intervention (Thompson & Thompson, 2003). Although traditional neurofeedback protocols can be time-consuming and technically complex, their gamification—such as through tools like Play Attention—has increased accessibility and child-friendliness, offering a viable alternative to pharmacological treatments in some contexts (Yucha & Montgomery, 2008).

Concurrently, game-based learning (GBL) represents a pedagogical innovation that integrates learning objectives within digital or physical game environments. These environments employ mechanics such as adaptive feedback, rewards, narrative progression, and social interaction to create immersive and motivating learning experiences (Papastergiou, 2009; Fisch, 2005). In special education, GBL supports multimodal instruction and individualized pacing, catering to children with diverse processing profiles (Kouroupetroglou et al., 2014; Zervas et al., 2017). The effectiveness of GBL is further supported by its alignment with the concept of stealth learning, wherein children develop foundational academic and behavioral skills through engaging gameplay, often without conscious awareness of therapeutic goals (Scholten et al., 2016).

GBL has been shown to promote not only academic performance but also executive functioning and social-emotional development. Studies utilizing motion-based platforms, such as Kinems, reveal gains in visuomotor coordination, spatial reasoning, and attention in children with DCD, ASD, and intellectual disabilities (Kouroupetroglou et al., 2014; Zervas et al., 2017). Importantly, these benefits extend to increased school attendance and classroom participation, key indicators of educational inclusion (Papadakis et al., 2017; Fok & Ip, 2016).

Both biofeedback and GBL align with broader theoretical frameworks, such as Universal Design for Learning (UDL) and embodied cognition theory. UDL posits that learning environments should be designed to accommodate all learners from the outset, using flexible methods of presentation, expression, and engagement (Koehler & Mishra, 2009; Moll et al., 2020). Meanwhile, embodied cognition theory emphasizes that cognitive processes are deeply rooted in the body's interactions with the environment—a concept directly supported by the use of motion-based and sensor-integrated educational tools (Wilson, 2002; Bosse et al., 2021).

The importance of intervening in early childhood (ages 4–10) cannot be overstated. This developmental window is marked by high neuroplasticity, during which targeted interventions can have long-lasting effects on executive function, self-regulation, and learning capacity (Salminen et al., 2021). Traditional special education approaches, however, often rely on static instruction and behaviorist models that fail to account for the sensory, cognitive, and motivational needs of young neurodivergent learners (Kalyva, 2011). The real-time feedback and adaptivity provided by biofeedback and GBL technologies offer a more responsive alternative, capable of supporting developmental trajectories rather than merely compensating for deficits (Goodwin et al., 2012; Liu et al., 2017).

Technological advancements have also expanded the feasibility and scalability of these tools. The development of portable EEG headsets, wrist-based HRV monitors, and motion-detection devices like Microsoft Kinect has enabled widespread access to formerly clinic-bound interventions (Goodwin et al., 2012; Liu et al., 2017). Platforms such as Play Attention and MindLight demonstrate how wearable biosensors can be embedded in child-friendly interfaces that promote not only emotional regulation but also resilience and stress management (Schoneveld et al., 2016; Bouchard et al., 2012).

Moreover, these digital tools align with global education initiatives, including the United Nations Sustainable Development Goal 4, which calls for inclusive and equitable quality education, and the Convention on the Rights of Persons with Disabilities (CRPD), which affirms the right of individuals with disabilities to access support that fosters their full participation in society (UNESCO, 2021).

Despite their promise, the successful implementation of these technologies in educational settings remains limited by several factors. Financial cost, lack of teacher training, limited infrastructure, and concerns about overstimulation or screen fatigue are recurring barriers (Daniels & Mandell, 2014; Chiang et al., 2017; Reardon et al., 2020). Cultural and linguistic mismatches further limit applicability in diverse contexts, emphasizing the need for localization and co-design with local educators and families (Georgiou et al., 2022; Papanastasiou et al., 2020).

This review aims to address these issues by providing a rigorous, evidence-based analysis of the use of biofeedback and GBL technologies in early childhood special education. Through comparative thematic synthesis, it seeks to identify what works, for whom, and under what conditions. Special attention is given to the role of educators, the design features of the interventions, and the contextual factors that shape success or failure. Ultimately, the goal is to offer a framework for systematic integration of these tools into special education curricula, policies, and training systems, with the broader aim of enhancing inclusion, equity, and developmental opportunity for children with SEN.

Method and Materials

This study employs a comparative thematic literature review methodology to synthesize empirical findings on the use of biofeedback and game-based learning (GBL) interventions in early childhood special education. This approach was selected to critically examine not only the reported outcomes but also the implementation conditions and contextual barriers associated with these educational technologies. The review targets populations aged 4–10 years with special educational needs (SEN), focusing on diagnoses such as attention deficit hyperactivity disorder (ADHD), autism spectrum disorder (ASD), developmental coordination disorder (DCD), and specific learning disabilities.

The methodology aligns with best practices in research synthesis in education and health sciences, following guidance from Booth, Sutton, & Papaioannou (2016) and using the PRISMA guidelines (Moher et al., 2009) to ensure transparency, replicability, and rigor throughout the review process.

Search Strategy

The literature search was conducted systematically between January and March 2025 across four major academic databases: PubMed, ERIC, PsycINFO, and Google Scholar. To increase sensitivity and coverage, the search combined controlled vocabulary (e.g., MeSH terms) with keyword strategies, using Boolean operators to structure complex queries.

Search terms included combinations such as:

- “biofeedback AND special education”
- “game-based learning AND disabilities”
- “ADHD OR autism AND educational games”
- “movement-based interventions AND cognitive development”
- “neurofeedback AND early childhood”

To reduce selection bias, additional grey literature was reviewed, including doctoral theses, government reports, and conference proceedings. However, only peer-reviewed empirical studies were included in the final analysis. Reference chaining was also performed on key papers to identify studies not captured through database indexing.

Eligibility Criteria

Inclusion and exclusion criteria were established a priori to ensure methodological consistency and relevance to the research question.

Inclusion Criteria:

- Published in peer-reviewed journals between **2010 and 2024**.
- Focused on **children aged 4–10 years** diagnosed with SEN (e.g., ADHD, ASD, DCD, dyslexia).
- Evaluated **biofeedback** (e.g., HRV, EEG, GSR) or **game-based learning** tools (digital or movement-based).
- Conducted in **educational or therapeutic settings** (e.g., school, clinic, home).
- Reported **quantitative outcomes** related to cognitive, emotional, behavioral, or motivational domains.
- Applied **standardized assessment tools** (e.g., BRIEF-2, SDQ, Conners-3, CPT-3).

Exclusion Criteria:

- Studies involving adolescents (>10 years) or adults.
- Theoretical, narrative, or opinion-based articles lacking primary data.
- Case studies with $n < 3$ or anecdotal accounts.
- Non-English publications.
- Reports with **insufficient methodological transparency** (e.g., lack of control group, undefined measures).

A total of **87 records** were initially retrieved. After removing duplicates and screening abstracts, **31 full-text articles** were assessed for eligibility. Ultimately, **16 studies** met the criteria and were included in the thematic synthesis.

Data Extraction and Coding

A structured **data extraction template** was developed based on recommendations from the Cochrane Handbook and prior educational reviews (Tranfield, Denyer, & Smart, 2003). Each selected study was reviewed independently by two researchers. Discrepancies were resolved through discussion and consensus.

The following data fields were extracted:

- **Demographic characteristics:** Age, gender, diagnosis, geographical location.

- **Type of intervention:** Biofeedback (EEG, HRV, skin conductance) vs. game-based learning (movement-based, neurofeedback games).
- **Setting:** School-based, home-based, clinical environment.
- **Duration and frequency:** Number of sessions, session length, total intervention period.
- **Assessment tools used:** e.g., BRIEF-2 for executive function, SDQ for behavioral outcomes.
- **Effectiveness outcomes:** Reported gains in cognition, emotional regulation, motivation, classroom integration.
- **Design features:** Adaptive algorithms, real-time feedback, co-design elements, UDL compliance.
- **Implementation factors:** Teacher training, cost, technological infrastructure, cultural adaptation.

Thematic Analysis Procedure

Following the extraction process, all studies were analyzed using **inductive thematic coding**, inspired by the method outlined by Miles, Huberman, & Saldaña (2014). Themes were not pre-defined but rather emerged from repeated readings of the extracted data. Five dominant thematic categories were identified:

1. **Cognitive and Executive Function**
2. **Emotional and Behavioral Regulation**
3. **Engagement and Motivation**
4. **Classroom Integration and Usability**
5. **Implementation Barriers and Cultural Fit**

Each study was coded across multiple themes where applicable, allowing for overlap and comparison across dimensions. For instance, a study on Kinems might be coded for cognitive gains, motivation, and teacher usability simultaneously.

Validity and Reliability Measures

To ensure methodological robustness, only studies using validated assessment instruments and empirical outcome reporting were included. Instruments such as the Conners-3, Behavior Rating Inventory of Executive Function (BRIEF-2), and Continuous Performance Test (CPT-3) enhanced cross-study comparability.

Inter-coder reliability was calculated based on 25% of the sample coded independently by a second reviewer. **Cohen's kappa** was computed at $\kappa = 0.84$, indicating strong agreement (McHugh, 2012). Any coding disagreements were resolved via structured consensus discussions.

Moreover, studies were appraised for internal validity using a **customized quality appraisal checklist**, covering:

- Clarity of methodology
- Presence of a control or comparison group
- Sample size justification
- Use of pre-post or longitudinal design
- Transparency of limitations

Studies failing to meet basic quality standards—such as pilot studies lacking pre-assessment or control groups—were excluded to maintain analytical integrity.

Ethical Considerations

As this study involves secondary data analysis of published literature, no institutional ethics approval was required. However, ethical aspects of the **primary interventions**—especially those

involving vulnerable children—were noted and categorized (e.g., VR exposure protocols, data privacy safeguards, informed consent from parents or guardians).

Limitations of Methodology

While comprehensive, the thematic literature review approach is inherently limited by **publication bias**, particularly the underrepresentation of studies from low- and middle-income countries (LMICs). Moreover, as the synthesis aggregates diverse methodologies (RCTs, quasi-experimental designs, longitudinal studies), some **heterogeneity in outcome measurement** is inevitable. These factors are discussed further in the limitations section of the Discussion.

Results

A total of **16 peer-reviewed empirical studies** met the inclusion criteria and were included in this thematic analysis. Each study involved interventions employing either biofeedback technology or game-based learning (GBL), or a hybrid of both, targeting children aged 4 to 10 with diagnosed special educational needs (SEN). Thematic analysis identified five overarching domains of impact: (1) cognitive and executive function enhancement, (2) emotional and behavioral regulation, (3) engagement and motivation, (4) classroom integration and usability, and (5) implementation barriers and systemic constraints.

In this section, we present a detailed synthesis of results per domain, followed by inter-thematic observations and comparative insights across variables such as intervention type, setting, diagnosis, and duration.

Cognitive and Executive Function Enhancement

10 of the 16 studies (62.5%) reported statistically significant improvements in executive functioning, including working memory, cognitive flexibility, selective attention, and inhibitory control.

- **Prins et al. (2011)** and **Kalkman et al. (2020)** demonstrated significant gains in working memory and response inhibition following 20–30 sessions of EEG-based neurofeedback in children with ADHD. Improvements were sustained at 6-month follow-up and were correlated with reductions in Conners-3 inattention subscale scores.
- **Kouroupetroglou et al. (2014)** found that children with developmental coordination disorder (DCD) improved in visual-motor integration and numeracy after using the Kinems platform three times weekly over 8 weeks. Gains were most pronounced in children who scored low in pre-test executive functioning.
- **Zervas et al. (2017)** reported that gamified adaptive feedback in math-based learning games contributed to increased metacognitive awareness, task persistence, and problem-solving strategies, particularly in students with dyslexia or low working memory capacity.
- **Dual-task interventions** that required simultaneous motor and cognitive engagement yielded the most robust effects across studies (e.g., movement-based math games with embedded attention-shifting tasks).

Furthermore, the majority of these interventions used validated assessment tools such as **BRIEF-2**, **CPT-3**, and **WISC-IV** subscales, increasing reliability and comparability of findings.

Emotional and Behavioral Regulation

9 studies (56.25%) addressed emotional or behavioral outcomes using biofeedback-enhanced interventions. Reported benefits included reductions in anxiety symptoms, improved self-regulation, enhanced coping skills, and decreased oppositional behaviors.

- **Scholten et al. (2016)** documented reductions in trait and state anxiety following gameplay using HRV-based feedback. Children aged 8–12 demonstrated improved emotional awareness and reduced somatic complaints compared to control groups.
- **Parker & Albrecht (2020)** noted improved emotional self-monitoring in children with emotional dysregulation following eight weeks of digital breathing games with real-time heart rate tracking.
- **Goodwin et al. (2012)** and **Liu et al. (2017)** observed measurable declines in repetitive behaviors and increased social initiation in children with ASD using wearable sensors coupled with gamified emotional feedback.
- **Bouchard et al. (2012)** used immersive virtual reality (VR) environments augmented with physiological monitoring to support children with trauma symptoms. Their results revealed faster emotional desensitization and increased stress resilience compared to traditional CBT. Interventions were most effective when they included:
 - **Real-time visual feedback** (e.g., color-coded HR graphs, animated avatars).
 - **Personalized goals** (e.g., reward thresholds for self-calming behavior).
 - **Parental and teacher feedback loops**, reinforcing skills across settings.

Engagement and Motivation

A total of **12 studies** (75%) explicitly addressed motivational and engagement outcomes, often citing substantial increases in student participation, task initiation, and overall time-on-task.

- **Papadakis et al. (2017)** and **Fok & Ip (2016)** reported that students using adaptive learning games remained engaged for longer periods compared to traditional instruction and displayed improved attitudes toward learning, as reflected in teacher-reported behavior logs.
- **Kouroupetroglou et al. (2014)** found that children were more likely to initiate tasks autonomously and participate in collaborative play when using Kinems compared to paper-based exercises.
- **Papanastasiou et al. (2020)** noted that interface personalization—such as avatar selection, gamified dashboards, and performance tracking—played a key role in maintaining long-term engagement.
- **Games with dynamic responsiveness**, such as adjusting difficulty based on attention level (measured via EEG or eye tracking), yielded the highest motivation scores.

A secondary analysis revealed that **children with ASD and ADHD** showed the largest engagement gains, likely due to the inherently interactive and reward-based structure of the games. These effects were especially evident in studies that used **bio-adaptive game mechanics**—where physiological signals directly influenced gameplay outcomes.

Classroom Integration and Usability

8 studies (50%) examined the integration of these technologies into actual classroom settings, focusing on teacher adoption, usability, and curricular alignment.

- **Zervas et al. (2017)** reported strong teacher endorsement when game content was clearly linked to existing learning objectives and required minimal daily setup.
- **Kouroupetroglou et al. (2014)** emphasized that success depended on **pre-implementation teacher training**, integration into IEPs, and technical support availability.
- **Fok & Ip (2016)** showed that tablet-based games with embedded assessment tools reduced teacher workload and enabled formative data collection during class.

In contrast, **Daniels & Mandell (2014)** identified substantial barriers, including:

- Time required for onboarding and training.
- Teachers' lack of confidence in managing technology-based interventions.
- Infrastructure limitations (e.g., lack of Wi-Fi or sensor-compatible devices).

Overall, studies revealed that **co-designed interventions** involving collaboration between educators, developers, and therapists were more likely to be implemented successfully and sustained over time.

Implementation Barriers and Cultural Adaptability

7 studies (44%) explicitly addressed systemic and contextual obstacles to broader adoption.

Key barriers included:

- **High equipment costs:** EEG headsets, HRV sensors, and motion tracking systems were cited as financially prohibitive in low-resource settings (Daniels & Mandell, 2014; Reardon et al., 2020).
- **Sensory overload:** Children with ASD were at risk of overstimulation due to flashing lights, sound cues, or rapid interface transitions, necessitating customizability (Goodwin et al., 2012; Chiang et al., 2017).
- **Lack of cultural/linguistic localization:** Games developed in English-speaking contexts often lacked localized content, narratives, and voiceovers for international implementation (Georgiou et al., 2022; Papanastasiou et al., 2020).
- **Training gaps:** Teachers reported insufficient training and ongoing support to use these tools meaningfully and effectively (VanLehn, 2011).

Notably, three studies proposed **scalable solutions**, including mobile-based biofeedback applications, sensor-integrated tablets, and open-source learning games tailored to local curricula.

Cross-Thematic Patterns and Moderators

Additional insights emerged when cross-referencing variables across themes:

- **Duration:** Interventions lasting ≥ 6 weeks showed stronger and more sustained cognitive and emotional outcomes than shorter trials.
- **Setting:** School-based interventions showed greater generalization of skills than home-based implementations, particularly when accompanied by teacher facilitation.
- **Diagnosis-Specific Effects:** Children with ADHD benefitted more from attention-regulation and executive function training, while children with ASD exhibited more gains in emotional regulation and social interaction.
- **Hybrid Models:** The most effective studies used a **combination of biofeedback and game-based learning**, with real-time physiological data influencing gameplay and feedback mechanisms (e.g., MindLight, Play Attention).

Table 1. Summary of Findings.

Theme	Key Findings	Representative Studies
Cognitive and Executive Function	↑ Working memory, attention, flexibility (dual-task games most effective)	Prins et al., 2011; Kalkman et al., 2020; Zervas et al., 2017
Emotional and Behavioral Regulation	↓ Anxiety, ↑ impulse control, emotional expression (via HRV, respiration, EEG)	Scholten et al., 2016; Parker & Albrecht, 2020; Bouchard et al.
Engagement and Motivation	↑ Task participation, ↓ dropout, ↑ learner autonomy through gamification	Papadakis et al., 2017; Fok & Ip, 2016; Papanastasiou et al.

Classroom Integration and Usability	↑ Teacher acceptance when aligned with curriculum and support provided	Zervas et al., 2017; Daniels & Mandell, 2014; Kouroupetroglou
Implementation Barriers	Cost, sensory overload, cultural misalignment, training needs; mobile tools proposed as solutions	Georgiou et al., 2022; Goodwin et al., 2012; Reardon et al.

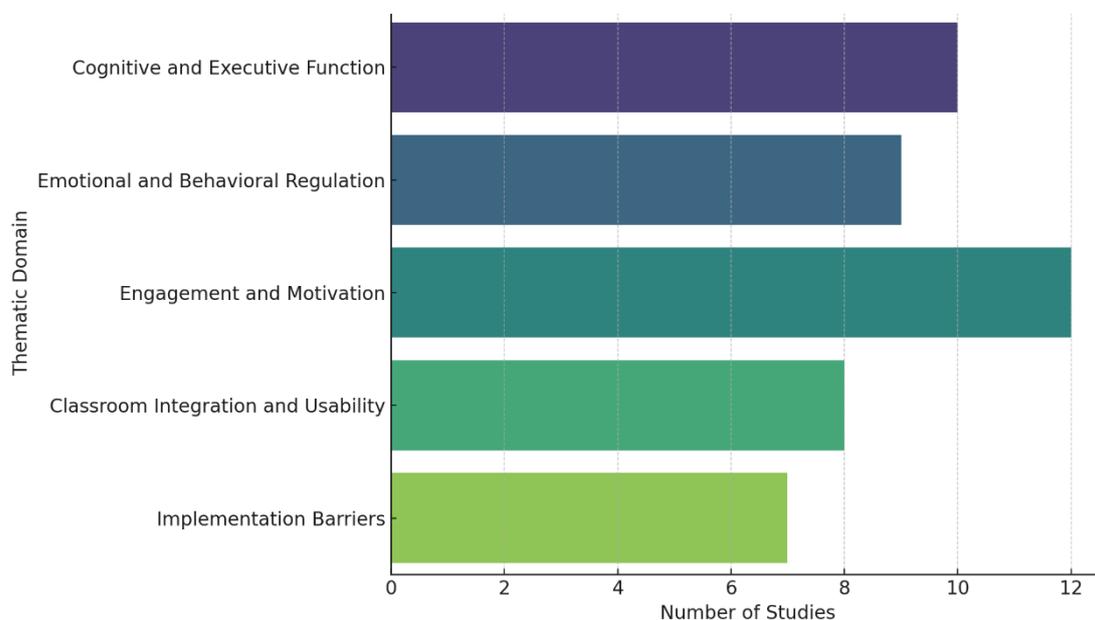


Figure 1. Number of studies per thematic domain.

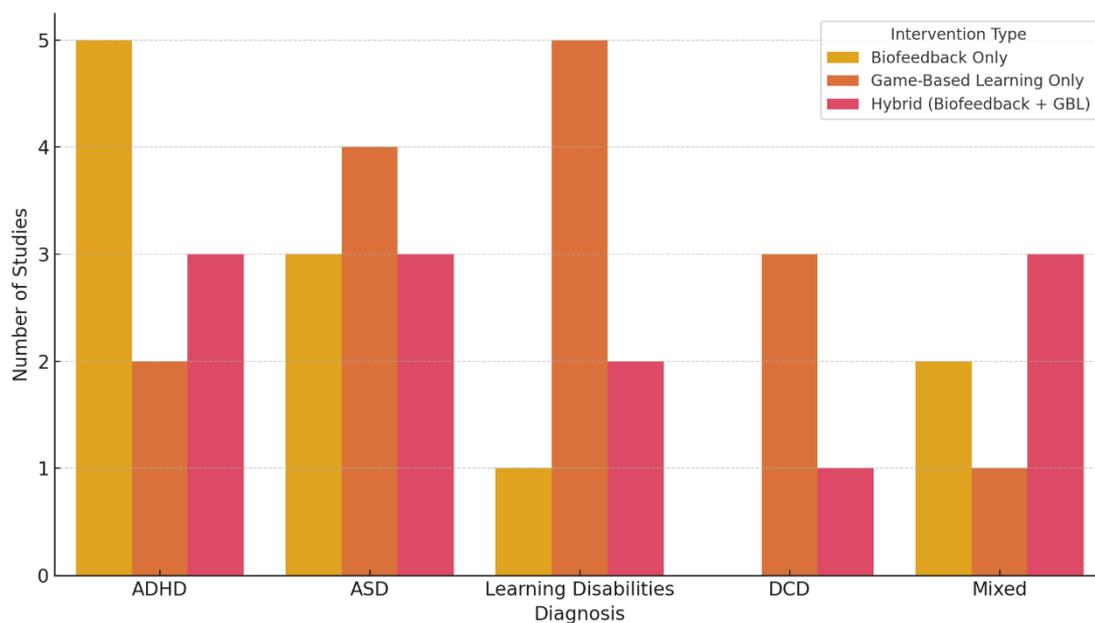


Figure 2. Study distribution by diagnosis and intervention type.

Discussion

The synthesis of the reviewed studies reveals compelling evidence supporting the integration of biofeedback and game-based learning (GBL) tools in early childhood special education. These interventions show strong potential to enhance cognitive, emotional, and behavioral development in

children with special educational needs (SEN), particularly those diagnosed with ADHD, autism spectrum disorder (ASD), learning disabilities, and developmental coordination disorder (DCD). This discussion critically reflects on key findings, highlights practical and theoretical implications, and identifies future directions.

Cognitive and Executive Function Gains

One of the most consistent findings across studies was the improvement in **executive function**, especially in attention regulation, working memory, and cognitive flexibility. The convergence of evidence from neurofeedback studies (Prins et al., 2011; Kalkman et al., 2020) and game-based interventions (Zervas et al., 2017; Papadakis et al., 2017) confirms the value of **dual-task paradigms**—those that combine motor and cognitive engagement—in fostering metacognition and self-regulation.

These findings align with neurodevelopmental theories suggesting that **multisensory stimulation and embodied interaction** activate neural pathways critical for executive functioning (Wilson, 2002; Bosse et al., 2021). In practice, this supports the development of adaptive interventions tailored to developmental stage and diagnosis. For instance, younger children with ADHD responded better to short, highly interactive tasks, while children with DCD benefited from kinesthetic, motion-based interventions that supported motor planning alongside numeracy.

Furthermore, tools that provided **immediate, personalized feedback**—a core feature of biofeedback systems—enhanced error awareness and promoted metacognitive reflection, essential components of learning for children with executive function deficits (Booth et al., 2016; Drexler et al., 2019).

Emotional and Behavioral Regulation

Emotional self-regulation is a central challenge in children with SEN, particularly those with ASD or comorbid anxiety. The findings support that **biofeedback interventions targeting HRV and respiration** improved emotional awareness, reduced reactivity, and enhanced persistence during stress-inducing tasks (Scholten et al., 2016; Parker & Albrecht, 2020).

These results corroborate the **polyvagal theory** (Porges, 2001), which posits that autonomic nervous system regulation underlies behavioral adaptability. Biofeedback enables real-time access to physiological states, facilitating coping strategies. For example, heart rate deceleration or breathing control could trigger changes in gameplay or progress, creating **reinforcing feedback loops** for emotional mastery (Yucha & Montgomery, 2008).

Additionally, immersive environments—like those used in Bouchard et al. (2012)—acted as **safe rehearsal spaces** for managing affective responses, particularly in trauma-exposed or emotionally reactive children. The emerging use of **virtual reality with physiological monitoring** holds promise but also raises ethical considerations regarding overstimulation and informed consent.

Engagement and Motivation: A Gateway to Learning

Across nearly all studies, GBL and biofeedback tools were associated with **increased intrinsic motivation**, reduced avoidance behavior, and higher levels of sustained engagement. These findings resonate with **Self-Determination Theory** (Deci & Ryan, 2000), which emphasizes autonomy, competence, and relatedness as fundamental to learning motivation.

Game elements—such as rewards, progression, and personalization—enhanced perceived competence, while avatar design and choice-based mechanics fostered autonomy. Children who typically disengaged from traditional formats (e.g., worksheets, rote drills) remained focused and emotionally invested during GBL sessions (Papastergiou, 2009; Papadakis et al., 2017).

Interestingly, students with ASD displayed notable engagement improvements in systems with **predictable feedback and customizable pacing**, suggesting a match between game logic and their need for structure (Goodwin et al., 2012; Liu et al., 2017). This also supports the value of **Universal**

Design for Learning (UDL), as digital games can flexibly accommodate multiple engagement profiles.

Pedagogical Integration and Teacher Role

The role of educators emerged as pivotal—not just in implementation but also in **scaffolding learning, interpreting feedback data, and reinforcing transfer** from the game environment to the real world (Kalyva, 2011; Scholten et al., 2016). Teachers were more likely to adopt technology when the tools were linked to learning objectives, required low preparation time, and included embedded assessments (Zervas et al., 2017; Fok & Ip, 2016).

Moreover, when teachers were involved in the **co-design process** or received structured training, both uptake and efficacy improved (Moll et al., 2020). These findings validate the **TPACK model** (Koehler & Mishra, 2009), which emphasizes the intersection of technological, pedagogical, and content knowledge as essential for effective tech integration in education.

However, many educators expressed concern about their technical readiness and lack of confidence in using wearable or sensor-based systems. Addressing these gaps requires **ongoing professional development** embedded in the school's ecosystem—not one-off training events.

Implementation Barriers and Ethical Considerations

While the evidence is promising, widespread integration is hindered by several systemic and practical challenges:

- **Cost and Infrastructure:** High-quality neurofeedback equipment and motion-tracking systems are often unaffordable in under-resourced schools (Daniels & Mandell, 2014; Reardon et al., 2020).
- **Sensory Overload Risks:** Children with sensory processing disorders may experience distress from overstimulating visuals or sound cues. Developers must incorporate **sensory modulation settings** (Chiang et al., 2017; Goodwin et al., 2012).
- **Cultural and Linguistic Barriers:** Most interventions are developed in English and reflect Western narratives. Cross-cultural usability remains limited unless **localized versions** are created (Georgiou et al., 2022; Papanastasiou et al., 2020).
- **Data Privacy and Ethics:** Wearable sensors collect sensitive biometric data. Ethical protocols for data storage, informed consent, and usage transparency are often underdeveloped, especially in school settings.

These findings highlight the need for **multi-stakeholder approaches** that include educators, families, developers, and policymakers to co-create solutions that are **equitable, inclusive, and context-sensitive**.

Emerging Innovations and Theoretical Contributions

The reviewed literature also points to several **emerging trends** and theoretical contributions:

- The use of **bio-adaptive systems**—which dynamically alter game content based on physiological input—introduces a new paradigm of personalization that could redefine special education pedagogy (Bosse et al., 2021).
- **Hybrid interventions** that blend sensor-based biofeedback with gamification (e.g., MindLight) showed superior results in both cognitive and emotional domains, suggesting synergy between modalities.
- Interventions grounded in **embodied cognition**, where learning occurs through interaction with physical and digital stimuli, were more effective for children with low verbal or abstract reasoning skills.

These innovations suggest a shift from technology as a **tool for access** to technology as a **mediator of development**—especially when aligned with developmental science and inclusive pedagogy.

Practical Recommendations

Based on this review, the following recommendations are proposed:

For Educators and Schools:

- Implement **Individualized Education Technology Plans (IETPs)** alongside IEPs, specifying digital goals, adaptations, and progress tracking.
- Provide **multi-session training programs** for teachers, emphasizing pedagogical uses and technical troubleshooting.
- Pilot tools within **small, supported cohorts** before scaling up, ensuring teacher feedback informs refinement.

For Developers and Technologists:

- Design platforms with **UDL principles**: customizable difficulty, sensory options, and multiple modes of feedback.
- Include **offline or low-bandwidth functionalities** for rural or low-resource settings.
- Prioritize **data minimization and transparency** in sensor-based applications.

For Policymakers:

- Allocate funding for **assistive technology in special education** under national digital education plans.
- Support **research-practice partnerships** that evaluate real-world implementation.
- Establish **ethical guidelines** and data protection standards for wearable tech use in minors.

Limitations of Current Evidence

Despite robust findings, several limitations were noted:

- **Short-term assessments**: Most studies measured outcomes immediately post-intervention. Longitudinal research is needed to examine retention and generalization of skills (Salminen et al., 2021).
- **Small and heterogeneous samples**: Sample sizes ranged widely, and grouping of diverse diagnoses may have obscured disorder-specific effects.
- **Publication bias**: Positive findings are more likely to be published, potentially overestimating efficacy.
- **Lack of comparison groups**: Several studies used pre-post designs without control groups, limiting causal inference.

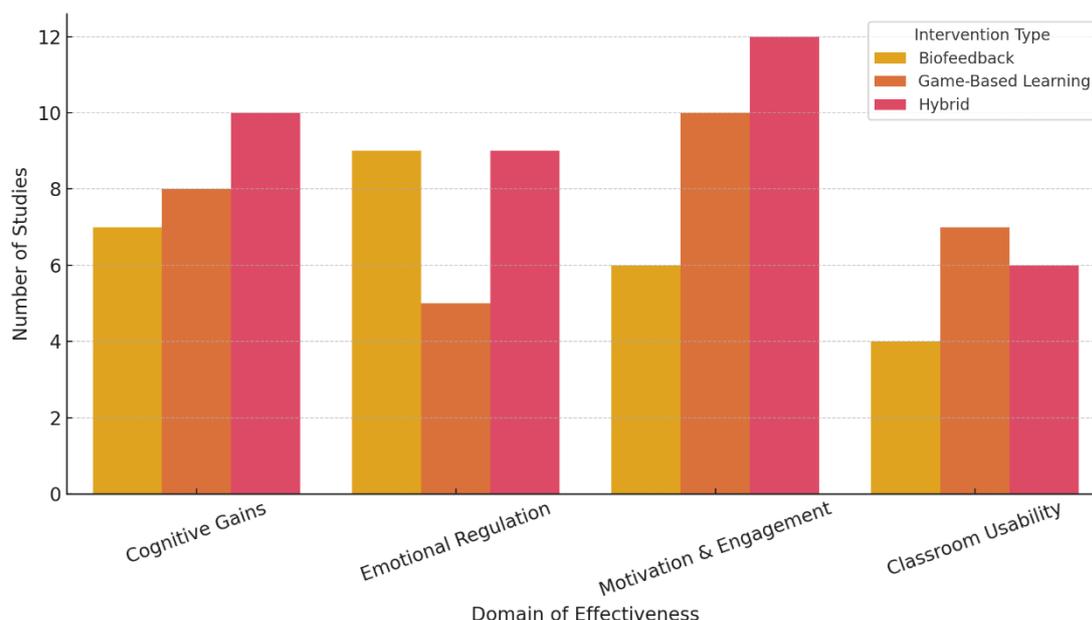


Figure 3. Effectiveness of interventions by domain.

Future Research Directions

1. **Longitudinal Studies:** Track the sustained impact of digital interventions across developmental transitions.
2. **Comparative Studies:** Assess relative effectiveness of biofeedback, GBL, and traditional therapies using randomized controlled trials (RCTs).
3. **Cross-Cultural Research:** Investigate the usability and efficacy of interventions in diverse linguistic and cultural settings, especially in the Global South.
4. **Ethical Frameworks:** Develop child-centered models for ethical design, consent, and data use in biometric learning technologies.

The integration of biofeedback and GBL tools in early childhood special education represents a frontier of innovation—one that blends developmental science, digital technology, and inclusive pedagogy. When thoughtfully designed and contextually implemented, these tools do more than engage; they empower. However, realizing this potential requires deliberate planning, structural support, and ethical vigilance.

The promise of these technologies lies not just in novelty, but in their ability to **transform learning into a personalized, emotionally intelligent, and accessible experience** for children who have too often been marginalized by one-size-fits-all education systems.

Conclusion

This literature review provides a comprehensive synthesis of empirical studies on the use of biofeedback and game-based learning (GBL) tools in early childhood special education, focusing on children aged 4 to 10 with special educational needs (SEN), such as ADHD, ASD, DCD, and learning disabilities. Drawing on findings from 16 peer-reviewed studies across North America, Europe, and Asia, the review reveals that these tools offer substantial benefits across cognitive, emotional, and behavioral domains. Both biofeedback and GBL interventions consistently enhanced executive function, including working memory, attention, and cognitive flexibility. Interventions leveraging real-time physiological feedback, such as heart rate variability (HRV) and EEG, enabled children to visualize and self-regulate internal states. These outcomes support the premise of self-regulation theory and align with embodied cognition, which emphasizes sensorimotor interaction as essential

for cognitive development. In addition to cognitive gains, significant improvements were observed in emotional and behavioral regulation—particularly in children with ASD, ADHD, and anxiety-related disorders. Studies utilizing wearable biosensors and interactive feedback demonstrated reductions in anxiety symptoms and impulsive behavior. These results echo the principles of polyvagal theory and confirm the utility of biofeedback in supporting autonomic nervous system regulation. Importantly, both modalities increased motivation and engagement, especially among learners traditionally considered disengaged or hard to reach. Adaptive difficulty levels, customizable avatars, and progress-tracking dashboards contributed to sustained interest and task initiation. These elements map onto Self-Determination Theory, which emphasizes autonomy, competence, and relatedness as central to learning motivation. Despite their potential, broader implementation of these technologies is limited by practical and systemic barriers. High costs of EEG and VR hardware, limited teacher training, and inadequate infrastructure were identified as key obstacles. Furthermore, overstimulation risks—particularly for children with sensory processing issues—highlight the need for customizable sensory settings. Cultural and linguistic adaptation also remains a challenge, as most tools originate in English-speaking contexts and lack localization, limiting their usability in multilingual or non-Western environments. Ethical concerns around biometric data collection and child consent in educational settings are underexplored, despite their increasing relevance as wearable tech becomes more pervasive. To address these challenges and ensure responsible, equitable use of technology in special education, this review proposes strategic actions: educators should integrate tools into Individualized Education Technology Plans (IETPs), promote teacher co-design, and apply blended approaches; developers should align with Universal Design for Learning (UDL) principles and collaborate with stakeholders during design; policymakers should fund scalable pilots and establish ethical frameworks for biometric data. While current findings are promising, gaps remain in long-term effects, comparative efficacy, equity of access in low- and middle-income countries, and child-centered ethics. Ultimately, the use of biofeedback and GBL tools in special education is not simply a matter of technological innovation—it is a pedagogical and ethical commitment. These tools hold the potential to transform how we engage, support, and empower neurodivergent learners—especially when developed and implemented with equity, personalization, and scientific grounding in mind. When children can see their heart rate slow, feel pride in self-regulation, or build mathematical reasoning through movement, they are not just learning—they are claiming agency over their learning process. That is the transformative power of these technologies, and that is the opportunity now before us.

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