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Effects of digital interventions on neuroplasticity and brain function of individuals with developmental disabilities: A systematic review

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ABSTRACT

Developmental disabilities (DDs) impact individuals' cognitive, psychological, and motor functions, and result in specific neural differences. Interventions to enhance neuroplasticity are important for this population. This review examined relevant existing studies to understand the effects of digital interventions on neuroplasticity and neural functions of individuals with DDs. A systematic review was conducted on PubMed, PsycINFO, CINAHL, and Scopus databases. Studies that focused on digital interventions to enhance neuroplasticity of individuals with DDs and used neuroimaging methods to evaluate effectiveness were included. The results of the current review were synthesized based on Roy's adaptation model. Of 3433 retrieved studies, 37 were included. The included studies used cognitive training, neuromodulation, and social cognitive training integrated with digital devices such as a computer, mobile app, or virtual reality. Neuroimaging results after digital interventions demonstrated changes in brain wave patterns and increased activation in certain regions. Behavioral assessments exhibited significant improvements including attention- deficit/hyperactivity disorder symptoms, attention, emotional recognition, and social skills. Digital interventions may enhance neural functions and neuroplasticity in individuals with DDs. Further studies with diverse methodologies and a broader spectrum of DDs are essential to fully understand the potential of digital interventions in neurodevelopmental challenges among the population.

1. Introduction

Developmental disabilities (DDs) are a spectrum of long-term conditions that impact individuals' cognitive, physical, psychological, language, and self-care capacities (American Psychiatric Association, 2013). The characteristics of brain function in individuals with DDs vary between people and by the type and severity of the disability. Nonetheless, commonalities in brain functions in DDs, including unfavorable levels of cognitive and social skills as well as perceptual–motor functions, have been identified (Porter and Campbell, 2021; Su et al., 2022; Yang et al., 2018).

Cognitive deficits in individuals with DDs manifest as impairments in executive functions, attention spans, and language competency (Demetriou et al., 2018; Hronis et al., 2017; Velikonja et al., 2019). These individuals also demonstrate weaknesses in the fundamental brain functions of emotion and behavioral regulation through various challenges, such as elevated anxiety and depression symptoms and aggressive behaviors compared to their counterparts without such disabilities (Hernández Lara et al., 2023; Mazzucchelli and Sanders, 2011; Shaw et al., 2014). Motor skills are contingent upon neural function and the interplay of physical practice with environmental feedback, and individuals with DDs consistently exhibit lower levels of motor planning, control, and coordination relative to those without DDs (Ku et al., 2020; Park et al., 2022).

Furthermore, various neuroimaging assessments have been employed to establish objective metrics for detecting abnormalities in brain structure and function in DDs, including structural magnetic resonance imaging (MRI), diffusion tensor imaging (DTI), functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and functional near-infrared spectroscopy (fNIRS) (Su et al., 2022). Research using neuroimaging assessments for individuals with DDs has identified unique features of the brain. The fMRI studies show distinct

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reductions in functional connectivity and activity within "social brain" regions (e.g., medial prefrontal cortex, superior temporal cortex, and amygdala) and in the cerebellum and corpus callosum, which play integral roles in modulating interactions within these social brain regions (McPartland et al., 2021). EEG studies have indicated deficits in event-related potentials (ERPs) which are associated with executive functioning, auditory and visual processing, and overall cognitive functioning. Additionally, certain changes in brain wave patterns indicative of attention-deficit hyperactivity disorder (ADHD) have been reported, distinguishing them from those of neurotypical control groups. Individuals with ADHD typically exhibit elevated relative theta power and reduced relative alpha and beta powers during resting EEG, along with increased theta/alpha and theta/beta ratios (Barry et al., 2003).

These pervasive neurological characteristics intrinsic to DDs exert a profound influence on every aspect of individuals' lives. This has resulted in a substantial body of research developing interventions to enhance neurological functions in individuals with DDs, designed to impact their neuroplasticity. Neuroplasticity, also known as brain plasticity, refers to the nervous system's ability to adapt in response to different stimuli, such as development, learning, environment, disease, and interventions; this process includes adaptive structural and functional changes in the brain (Cramer et al., 2011; Puderbaugh and Emmady, 2024).

Research suggests the positive effects of interventions aimed at enhancing neuroplasticity in individuals with DDs (Cramer et al., 2011). For example, neuroplasticity is facilitated by invasive/non-invasive brain stimulation techniques, including transcranial magnetic stimulation and electrical current application via implanted electrodes (Cramer et al., 2011). Physical training and exercise interventions, such as constraint-induced movement therapy, aerobic exercise, and circuit-based training, are recognized as effective strategies for inducing positive neural effects in individuals with DDs (Cramer et al., 2011; Su et al., 2022). Additionally, cognitive trainings, such as meditation-based therapy and cognitive behavioral therapy (CBT), have been empirically reported to enhance various cognitive functions (e.g., inattention, working memory, inhibition, and executive functions) in individuals with DDs (Lambez et al., 2020). These interventions promote neuroplasticity through synaptic strengthening, neurogenesis, and cortical reorganization. For instance, aerobic exercise increases the expression of brain-derived neurotrophic factor (BDNF), supporting synaptic plasticity and cognitive function (Kumar et al., 2023). Cognitive training programs encourage both structural and functional neuroplastic changes via repetitive and targeted stimulation, which not only strengthen neural connectivity and cortical thickness but may also mitigate structural and functional abnormalities commonly associated with neurodevelopmental disorders, such as reduced grey matter volume in ADHD and aberrant network connectivity in individuals with mathematical learning disability (Weyandt et al., 2020).

With the development of digital technologies, research on technology-integrated interventions to enhance neuroplasticity in individuals with DDs has been increasing (Kokol et al., 2020). Studies employing digital technologies such as games and virtual reality (VR) showed positive effects on brain functions, including cognitive functions and motor skills, in individuals with DDs (Park et al., 2022). In addition to demonstrating effectiveness, digital interventions offer distinct advantages compared to in-person interventions. Digital interventions allow individuals to access and engage with interventions at their preferred time and location, enhancing accessibility and engagement, particularly for those with DDs who may experience difficulties visiting unfamiliar places (Marcu et al., 2022). Moreover, digitally delivered interventions ensure consistent delivery of programs without facilitator variability and allow for scalability to reach larger and more diverse populations (Erasmus et al., 2025). Despite the efforts to incorporate interventions facilitated by digital devices, a comprehensive synthesis of research outcomes from the relevant studies is absent (Vacca et al., 2023). Therefore, this study explored the contribution of digital interventions to enhance neuroplasticity in individuals with DDs. It also synthesized data on digital interventions to enhance neuroplasticity and brain functioning of the population based on Roy's Adaptation Model (RAM), which elucidates how individuals adapt to environmental changes to maintain health and wellness (Roy and Andrews, 1999).

2. Methods

This systematic review followed the Joanna Briggs Institute methodology (Aromataris et al., 2015) to explore the effects of digital interventions on brain functions of individuals with DDs. The protocol was registered under the International Prospective Register of Systematic Reviews (PROSPERO) (CRD42023452565).

2.1. Selection criteria

The inclusion criteria were defined based on the population, intervention, comparison, outcomes, and study type (PICOS) framework. The population included individuals diagnosed with developmental disabilities, defined as chronic conditions that originate due to an impairment in physical, learning, language, or behavior areas during the developmental period, typically spanning birth through adolescence (Centers for Disease Control and Prevention, 2024). These disabilities included, but were not limited to, ADHD, autism spectrum disorder (ASD), dyslexia, and dyscalculia. No age restrictions were applied, and individuals were included regardless of their age at the time of the intervention, provided the condition originated during the developmental period.

Interventions comprised digital interventions targeting neuroplasticity and brain functions in individuals with DDs. These interventions were delivered through various digital platforms, including computers, mobile applications, VR, and wearable devices (World Health Organization, 2023). Therapeutic strategies encompassed cognitive training, physical activity programs, neurofeedback, and brain stimulation techniques, tailored to each platform's capabilities and the targeted neural functions (Cramer et al., 2011; Lambez et al., 2020). Comparisons could be either with in-person interventions or other control interventions. Articles without a comparison were also included, reflecting the review's attempt to comprehensively investigate digital interventions, rather than solely identifying their relative effects.

Outcomes were primarily brain functions measured via neuroimaging technologies, including EEG, MRI, and fMRI. Articles that did not measure brain functions or neural patterns with such modalities were not included. However, other additional measurements and their outcomes in the relevant studies were considered to provide integrated results. Some additional outcomes included symptoms related to the disabilities or task performance. All were included as long as they provided reliable evidence, which in this review refers to the use of scientifically validated and widely accepted measurement tools to assess neurophysiological or behavioral outcomes. Only articles with full text in English were included, while qualitative studies, clinical guidelines, and review articles were excluded. This review included all types of empirical studies that provided original data based on human participants. Eligible designs included randomized controlled studies, non-randomized controlled studies, and case studies.

2.2. Search strategy

A comprehensive literature search was conducted on the following online databases: PubMed, PsycINFO, CINAHL, and Scopus. Search terms employed three primary groups based on preliminary scoping search and existing knowledge regarding the topic: (1) diagnostic terms, which were related to neurodevelopmental disorders (e.g., "Autism spectrum disorder," "Attention-deficit/hyperactivity disorder," "Developmental coordination disorder," "Learning disorder," and "Intellectual disorder"); (2) intervention terms, related to digital interventions (e.g., "Digital" and "Computer"); and (3) neuroimaging terms, related to neuroimaging modalities (e.g., "Electroencephalography," "Magnetic resonance imaging," and "Near-infrared spectroscopy"). The search strategy was developed in collaboration with the librarian of Yonsei Medical Library (Supplementary material 1). The last search for these studies was completed April 16, 2025.

2.3. Study selection

The search results were imported into Covidence ("Covidence," n.d.), a web-based program for systematic review management. After eliminating duplicates, the titles and abstracts were screened, followed by the full article texts. At each stage, two reviewers independently determined each article's eligibility based on the preset criteria. Any conflicts between the two reviewers were resolved by the corresponding author. Cohen's kappa for the full-text review stage was 1.00, indicating perfect agreement (Belur et al., 2021).

2.4. Quality assessment

Quality assessment criteria were accorded based on the Mixed Methods Appraisal Tool (MMAT) (Hong et al., 2018) version 2018 to ensure the quality of the included studies. This tool evaluates empirical studies of different designs that are included in a systematic review, and offers distinct checklists for each study design, thereby enhancing precision in assessment. Based on answers ("yes," "no," or "can't tell") to five questions, a score ranging from 0 % to 100 % is obtained for each article. In this study, two researchers cross-evaluated each article to determine its eligibility. Inter-rater agreement for the MMAT-based quality assessment yielded a Cohen's kappa of 0.63, indicating substantial agreement (Belur et al., 2021).

Of 37 retrieved studies, 11 were evaluated using the randomized controlled trial (RCT) checklist, while the remaining 26 were assessed with the non-RCT checklist. Among the RCTs, six studies (55 %) scored 100 %, four studies (36 %) scored 80 %, and one study (9 %) scored 60 %. Of the 26 non-RCTs, nine studies (35 %) scored 100 %, seven studies (27 %) scored 80 %, six studies (23 %) scored 60 %, and four studies (15 %) scored 40 %. The detailed results of the quality assessment can be found in Supplementary material 2.

2.5. Data extraction and synthesis

From the PDF of each included study, the data were systematically extracted using a structured template. The data encompassed purpose, design, participant demographics, interventions, and outcomes of each study. Each member of the research team thoroughly examined the extracted data for accuracy and completeness. After a discussion aimed at achieving consensus, the corresponding author implemented the necessary revisions.

This study used the key concepts of RAM (Roy and Andrews, 1999) to organize and visually represent the extracted data regarding the interventions. The RAM is a conceptual framework that assesses the adaptation level of an individual or group, which is a result of the coping strategies employed to manage internal or external stimuli. It has been widely utilized as a theoretical framework in studies examining the effects of interventions for people with chronic health conditions (Kim et al., 2020; Mansouri et al., 2019). The RAM views human beings as adaptive systems that strive to achieve a state of adaptation, which entails being integrated in their surrounding environment. When exposed to various stimuli, a human being, or the adaptive system, activates coping strategies to respond effectively and finally enhance its adaptation.

In this study, digital interventions corresponded to external stimuli to the adaptive system. The target brain functions of these interventions were matched with the coping strategies of the adaptive system. The observed adaptive or maladaptive responses were reflected in the neuroplasticity of the participants.

3. Results

3.1. Study characteristics

The initial literature search yielded 3433 studies. After removing duplicates, the titles and abstracts of 2297 studies were screened; thereafter, the full texts of 88 articles were reviewed. Finally, 37 studies met the inclusion criteria (Fig. 1).

The characteristics of the selected studies are outlined in Table 1. The included literature spanned from 1996 to 2025, with studies over the last five years (2020–2025) constituting 51 % (n = 19), indicating a significant recent increase in research. The majority of studies (n = 9) were conducted in the United States, followed by Germany (n = 5), South Korea (n = 3), and Spain (n = 3). Other countries included China, India, and Singapore with two studies in each. Pretest–posttest design was the most prevalent (n = 13), followed by RCTs (n = 11) and pretest–posttest pilot studies (n = 7). Additionally, there were three case studies (n = 3), two posttest studies (n = 2), and one pilot RCT.

3.2. Participant characteristics

The systematic review encompassed 1613 participants, with 1316 in the intervention group and 297 in the control group. Sample sizes varied from 1 to 560 participants. Among the included articles, the majority (n = 18) focused exclusively on participants with ADHD, followed by 13 studies on ASD and 3 on dyslexia. Additionally, individuals with developmental dyscalculia and Down syndrome were each targeted in one study (Kucian et al., 2011; Lopes et al., 2022). Ha et al. (2022) included participants with both ADHD and intellectual disabilities. The participants' age ranged from 6 to 65 years, with 81 % (n = 30) studies targeting participants under the age of 20.

3.3. Synthesis of the results according to the RAM

3.3.1. Stimuli

According to RAM, stimuli are conceptualized as inducers of responses within the system (Roy and Andrews, 1999). This review operationalized the concept of "stimuli" as digital interventions targeted at influencing neural functions in individuals with DDs. The digital interventions identified in this review were cognitive training (n = 18), neuromodulation (n = 13), and social cognitive training (n = 7). As Luo et al. (2023) implemented both cognitive training and neuromodulation, this accounts for the total number of interventions exceeding the number of individual studies.

To deliver these interventions, the studies employed digital devices including computers (n = 21), VR (n = 9), and mobile applications (n = 7) (Fig. 2 and Table 2).

Cognitive training was the most frequently-used intervention, comprising methods such as memorizing cards, practicing calculations, or responding right signals; these interventions predominantly targeted individuals with ADHD (n = 12), but they also extended to those with dyslexia (n = 3), ASD (n = 2), developmental dyscalculia, and intellectual disabilities. Cognitive training interventions were primarily delivered in the form of games. For instance, in Johnstone et al. (2010), individuals with ADHD were required to rapidly make "Go"/"No go" decisions upon viewing a picture that indicated a "Go" response on a computer monitor. The participants had to click on boxes to reveal hidden bananas, which were then fed to a monkey. Additionally, cognitive training was implemented as VR art therapy, where participants engaged in geometric art drawings within an immersive environment (Peng and Leong, 2024). On average, cognitive training interventions were provided over 3 to 12 weeks, with a total of 3 to 36 sessions. The sessions lasted between 15 and 30 min, indicating relatively shorter durations compared to neuromodulation and social

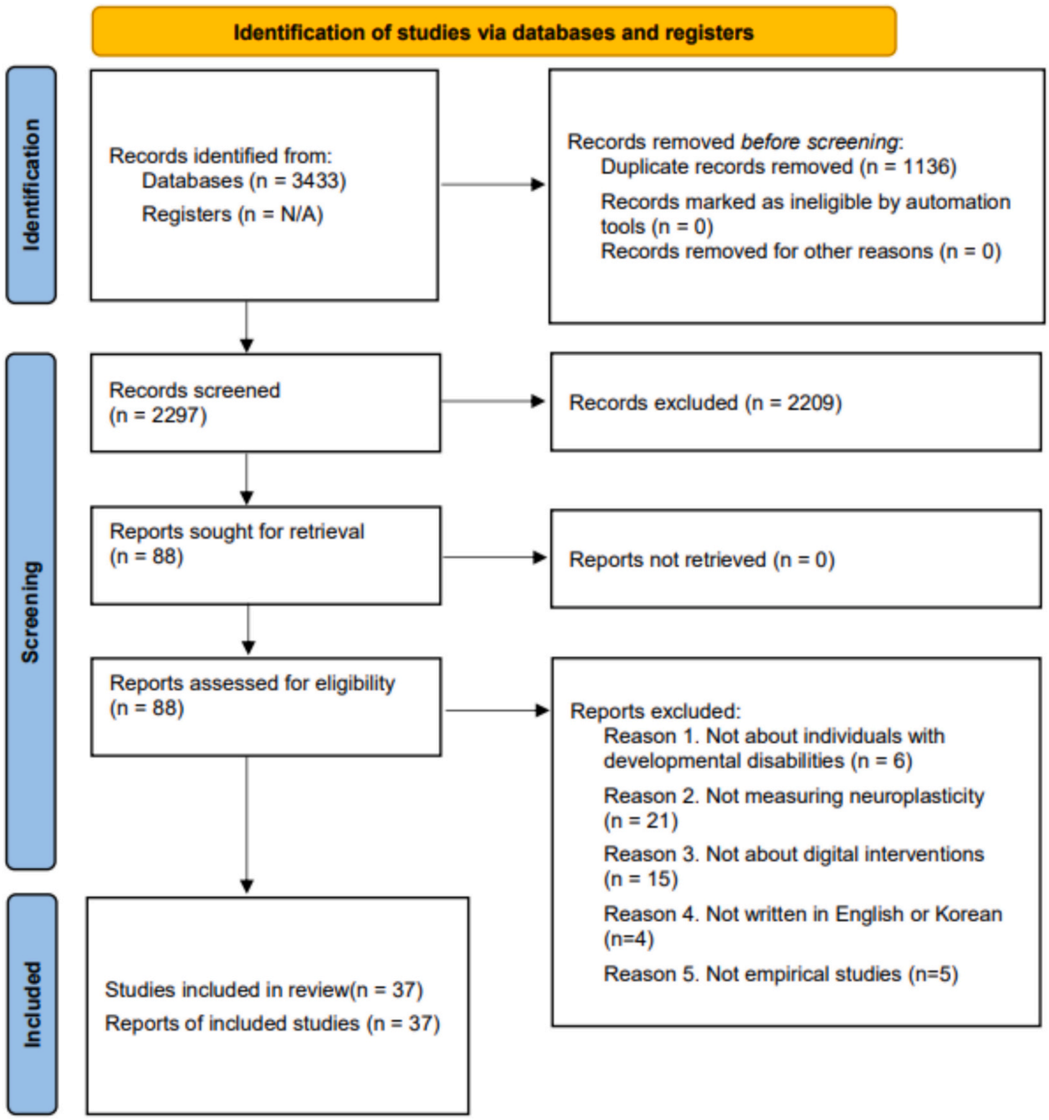

Fig. 1. PRISMA chart flow.

cognitive training.

Neuromodulation was the intervention in 13 studies, with eight targeting individuals with ADHD, four focusing on those with ASD, and one involving individuals with Down syndrome. Neuromodulation refers to techniques that modulate neural activity through electrical, sensory, or feedback-based stimulation to induce functional changes in the brain. Traditionally, neuromodulation referred primarily to stimulation techniques such as deep brain stimulation and non-invasive approaches such as transcranial direct current stimulation (tDCS) (Helena et al., 2021). However, recent literature increasingly includes neurofeedback and brainwave entrainment as forms of non-invasive neuromodulation, as they aim to modulate neural activity through real-time feedback or rhythmic sensory stimulation (Cidral-Filho et al., 2025; Sulzer et al., 2024). Based on these classifications, the present review categorized neurofeedback (n = 9), tDCS (n = 3), and brainwave entrainment (n = 1) under the neuromodulation intervention type. Neuromodulation interventions can be distinguished by the mode through which stimulation is delivered to the brain. In neurofeedback, participants perform specific tasks while receiving auditory or visual feedback in real time, based on changes in their brainwave activity measured via EEG (Jiang and Johnstone, 2015). In the case of tDCS, participants engage in cognitive or social cognitive tasks while simultaneously receiving low-intensity electrical stimulation intended to modulate cortical excitability (Chan et al., 2023). Brainwave entrainment has also been implemented in a virtual reality (VR) environment. Unlike neurofeedback, which is contingent on real-time EEG signals, this intervention delivered consistent optical and auditory rhythmic stimuli independent of the participant's ongoing brain activity. Specifically, participants experienced 10 Hz visual pulses (white light) embedded in immersive 360° VR videos depicting birds and animals, combined with 10 Hz binaural beats delivered via earphones (Mandapati and Ranjan, 2025).

Across these approaches, the stimuli or feedback were designed to normalize atypical brainwave patterns and enhance neural activation associated with the targeted cognitive or social functions. Neuromodulation session durations ranged from 15 min to 1 h and were conducted between 2 and 40 times. The total duration of intervention ranged from 2 days to 24 weeks.

All seven studies employing social cognitive training targeted individuals with ASD. Social cognitive training was mainly delivered to train facial affect recognition. Additionally, it involved learning appropriate behaviors in scenarios resembling virtual social situations. In two studies, researchers employed the Frankfurt Training for Facial Affect Recognition, a computer-based social cognitive training program (Bölte

Table 1
Characteristics of the included studies.

	Country	Study design	Purpose	Sample: N (mean years, %male) - Races/ethnicity		Intervention		Outcomes	Measurement related to brain	Main findings
				Experimental	Control	Experimental	Control			
Kotwal et al. (1996)	United States	Case study	To assess the use of computer-administered cognitive training software with patients in the treatment of ADHD[a]	ADHD: 1 (13 years, % male: 100) - Not reported	–	Computer-based cognitive training for cognitive skills	–	Behavioral problems, cognitive skills, neural pattern	EEG[b]	△
Pop-Jordanova et al. (2005)	Republic of Macedonia	Pretest-posttest study	To evaluate the effect of neurofeedback treatment on ADHD patients	ADHD: 12 (9 years, % male: 91.67) - Not reported	–	Computer-based neuromodulation with neurofeedback for cognitive skills	–	ADHD symptoms, intelligence level, social skills, school performance, neural pattern	EEG	O
Bölte et al. (2006)	Germany	RCT[c]	To evaluate the effect of the Frankfurt Test for Facial Affect Recognition training by activating the fusiform gyrus	ASD[d]: 5 (29.4 years, % male: 100) - Not reported	ASD: 5 (25.8 years, % male: 100) - Not reported	Computer-based social cognitive training for social skills	–	Emotional recognition, brain activity	fMRI[e]	O
Winn et al. (2006)	United States	Pretest-posttest study	To determine whether dyslexic children in grades 4–6 can build accurate and useful mental models of complex natural phenomena from an interactive computer simulation supported by a nonverbal curriculum.	Dyslexic: 12 (9-11 years) - Not reported	TD[f]: 12 (9-11 years) - Not reported	Computer-based cognitive training (simulation program) for language skills	Computer-based cognitive training (simulation program) for language skills	Cognitive skills, language skills, brain activity	fMRI	O
Johnstone et al. (2010)	Australia	RCT	To examine the effect of a computer-based cognitive training program with performance-sensitive, variable difficulty on ADHD children	ADHD: 15 (10.7 years, % male: 86.21) - Not reported	ADHD: 14 (10.7 years, % male: 85.71) - Not reported	Computer-based cognitive training for cognitive skills with high-intensity condition	Computer-based cognitive training for cognitive skills with low-intensity condition	Working memory, response inhibition, reported ADHD symptoms, neural pattern	EEG	O
Kucian et al. (2011)	Switzerland	Pretest-posttest study	To evaluate a custom-designed training program in dyscalculic children	Developmental Dyscalculia: 16 (9.5 years, % male: 37.5) - Not reported	TD: 16 (9.5 years, 43.75 %) - Not reported	Computer-based cognitive training for cognitive skills	–	Calculation performance, brain activity	fMRI	O
Lee and An (2011)	South Korea	Pretest-posttest study	To measure the effectiveness of a multimedia intervention program for ADHD children	ADHD: 4 (10–12 years) - Not reported	–	Computer-based cognitive training for cognitive skills	–	Neural pattern	EEG	O
Lim et al. (2012)	Singapore	Pretest-posttest study	To evaluate the new version of the BCI[g]-based attention training program with a game, CogoLand, in the treatment of ADHD	ADHD: 20 (7.8 years, % male: 80 %) - Not reported	–	Computer-based cognitive training for cognitive skills	–	ADHD symptoms, neural pattern	EEG	O
Russell-Chapin et al. (2013)	United States	Pilot RCT	To examine the effect of neurofeedback on ADHD and functional changes in the default mode network	ADHD: 6 (12.4 years, % male: 91.67) *Age and % male - from all 12 subjects - Not reported	ADHD: 6 (12.4 years, % male: 91.67) - Not reported	Computer-based neuromodulation with neurofeedback for cognitive skills	–	Neural pattern	fMRI, EEG	O
Bölte et al. (2015)	Germany	Pretest-posttest study	To determine whether improvements in facial affect recognition following computer-aided cognitive training in ASD are accompanied by an activation of the social brain	ASD: 16 (19.3 years, % male: 100) - Not reported	ASD: 16 (19.3 years, % male: 87.5) TD: 25 (19.7 years, % male: 84) - Not reported	Computer-based social cognitive training for social skills	–	Emotional recognition, brain activity	fMRI	O
Jiang and Johnstone (2015)	China	Case study	To evaluate the feasibility of combined cognitive and neurofeedback training on the behavior of ADHD children	ADHD: 5 (9.2 years) - Not reported	–	Computer-based neuromodulation with neurofeedback for cognitive skills	–	ADHD symptoms, behavioral problems, neural pattern	EEG	O

(*continued on next page*)

Table 1 (*continued*)

	Country	Study design	Purpose	Sample: N (mean years, %male) - Races/ethnicity		Intervention		Outcomes	Measurement related to brain	Main findings
				Experimental	Control	Experimental	Control			
Bekele et al. (2016)	United States	Pretest-posttest study	To design and develop an innovative adaptive multimodal VR[h]-based social interaction platform for ASD intervention	ASD: 6 (15.77 years, % male: 100) - Not reported	ASD: 6 (15.20 years, % male: 100) - Not reported	VR-based social cognitive training for social skills with online gaze feedback and occlusion paradigm	Sham intervention	Emotional recognition, the neural pattern	EEG	△
Chung et al. (2016)	South Korea	RCT	To evaluate the effect of a prosocial online game on social cognition in ASD and the association with brain activity	ASD: 10 (15.8 years, % male: 80) - Not reported	TD: 10 (16.3 years, % male: 90) - Not reported	Computer-based social cognitive training with CBT[i] for social skills	Offline-CBT	Social skills, brain activity	fMRI	△
Koen et al. (2018)	United States	Pretest-posttest study	To evaluate changes in brain activity and fluency scores after visual hemisphere-specific stimulation training in dyslexic students	Dyslexic: 9 (15 years, % male: 88.89) - Race: African American (1, 11 %), Anglo (8, 89 %)	Dyslexic: 6 (113 years, % male: 33.33) - Race: African American (2, 33 %), Anglo (4, 67 %)	Computer-based cognitive training for language skills	The usual reading fluency program	Fluency performance, brain activity	fMRI	O
Qian et al. (2018)	Singapore	RCT	To examine the changes of brain functional networks after a BCI based attention intervention in ADHD	ADHD: 18 (9 years, % male: 100) - Not reported	ADHD: 11 (9.45 years, % male: 100) - Not reported	Computer-based cognitive training for cognitive skills	–	ADHD symptoms, behavioral problems, brain connectivity	fMRI	O
Yang et al. (2018)	United States	Pretest-posttest study	To elucidate the neural mechanisms underlying behavioral changes in ASD adolescents after VR-Social Cognition Training	ASD: 17 (22.50 years, % male: 88.23) - Not reported	–	VR-based social cognitive training for social skills	–	Emotion recognition, socio-cognitive processing abilities, brain activity	fMRI	O
Georgiou et al. (2019)	Spain	Pretest-posttest pilot study	To document the findings of the REEFOCUS game, an intervention program for ADHD children	ADHD: 64 *EEG data for 53 (9.98 years, % male: 75.47) - Not reported	–	VR-based cognitive training for cognitive skills	–	Attention, the neural pattern	EEG	O
Pereira et al. (2019)	Chile	Pretest-posttest pilot study	To train ASD patients with real-time fMRI-neurofeedback and investigate the neural effects in the fusiform face area	ASD: 5 (16.52 years, % male: 100) - Not reported	Control 1) TD: 3 (29.42 years, % male: 100) Control 2) TD: 3 (35.21 years, % male: 100) - Not reported	Computer-based neuromodulation with neurofeedback for cognitive skills	Sham intervention	Brain activity	fMRI	O
Meyer et al. (2020)	United States	RCT	To test the effects of inhibitory control training in ADHD children	ADHD: 20 (9.84 years, % male: 65) - Not reported	ADHD: 20 (10.82 years, % male: 75) - Not reported	Computer-based cognitive training for cognitive skills (adaptive version)	Sham intervention	ADHD symptoms, neural pattern	EEG	O
Rosenblau et al. (2020)	Germany	RCT	To test the effect of social-cognitive training on neuroplasticity in ASD adults	ASD: 25 (34.5, % male: 76) - Not reported	ASD: 23 (30.2, % male: 56.52) - Not reported	Computer-based training program for social skills	Non-social online game	Emotional recognition, Social skills, brain activity	fMRI	O
Chrisilla et al. (2021)	India	Posttest study	To evaluate the effect of VR environment on cognitive learning abilities in normal and ASD children	ASD: 3 (6–10 years) - Not reported	TD: 3 (6–10 years) - Not reported	VR-based social cognitive training for cognitive skills	VR-based social cognitive training for cognitive skills	Brain connectivity, learning skills	EEG	O
De Luca et al. (2021)	Italy	Pretest-posttest pilot study	To assess changes in cognitive functions in ASD children after virtual reality therapy and determine its neurophysiological mechanisms	ASD: 20 (11 years, % male: 35) - Not reported	–	VR-based cognitive training for cognitive skills	–	Attention, problem-solving, abstract thinking, visuospatial integration, anxiety, brain connectivity	EEG	O
Gallen et al. (2021)	United States	Pretest-posttest pilot study	To examine neural markers of attention and test the effect of a digital therapeutic in ADHD children	ADHD: 25 (10.44 years, % male: 80) - Not reported	–	Mobile app-based cognitive training game for cognitive skills	–	ADHD symptoms, neural pattern	EEG	O

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Table 1 (*continued*)

	Country	Study design	Purpose	Sample: N (mean years, %male) - Races/ethnicity		Intervention		Outcomes	Measurement related to brain	Main findings
				Experimental	Control	Experimental	Control			
Medina et al. (2021)	Spain	RCT	To examine the neurocognitive effectiveness of cognitive stimulation therapy in ADHD patients	ADHD: 15 (9.2 years, % male: 86.67) - Not reported	ADHD: 14 (9.71 years, % male: 85.71) - Not reported	Computer-based cognitive training for cognitive skills	Sham intervention	Cognitive skills, executive function, ADHD symptoms, neural pattern	MEG[j]	O
Bluschke et al. (2022)	Germany	Pretest-posttest pilot study	To examine the effects of different EEG frequency band neurofeedback protocols on the cognitive functions in ADHD patients	ADHD:129 (10–11 years) - Not reported	–	Computer-based neuromodulation with neurofeedback for cognitive skills	–	ADHD symptoms, neural pattern	EEG	O
Ha et al. (2022)	South Korea	Pretest-posttest pilot study	To investigate the feasibility of mobile application-based interventions in ADHD and ID[k] children	ADHD: 12 ID: 9 (6.69 years, % male: 52.38) - Not reported	–	Mobile app-based cognitive training for cognitive skills	–	Attention, executive function, ADHD symptoms, neural pattern	EEG	O
Lopes et al. (2022)	Brazil	Pretest-posttest study	To investigate neurophysiological changes in motor behavior following tDCS[l] combined with VR training in DS[m] patients	DS: 12 (18 years) - Not reported	–	VR-based neuromodulation with anodal tDCS for cognitive and motor skills	–	Kinematic data, neural pattern	EEG	O
Luo et al. (2023)	China	RCT	To compare the effects of different combinations of neurofeedback and computerized cognitive training in ADHD children	ADHD: 80 (8.94 years, % male: 82.5) - Not reported	–	Mobile app-based cognitive training and neurofeedback for cognitive skills	–	ADHD symptoms, inhibitory control, working memory, neural pattern	EEG	O
Whitehead et al. (2022)	Canada	Pretest-posttest pilot study	To assess the efficacy of app-based remote neurofeedback training in improving cognition in ADHD patients	ADHD: 63 TD: 497 (13+ years) - Not reported	–	Mobile app-based neuromodulation with neurofeedback for cognitive skills and mental health	–	ADHD symptoms, general mental health condition, neural pattern	EEG	O
Junttila et al. (2023)	Finland	Pretest-posttest study	To compare the effectiveness of game vs non-game digital language training program in causing plasticity in dyslexic children	Dyslexic: 24 (9 years, % male: 42.67) - Not reported	TD: 24 (9 years, % male: 42.67) - Not reported	Mobile app-based cognitive training for language skills	Mobile app-based cognitive training for language skills	Language skills, reasoning, short-term memory, neural pattern	EEG	O
LaMarca et al. (2023)	United States	Case study	To determine if ASD children would show improvements in symptoms and mu suppression following mu-neurofeedback	ASD: 7 (6–8 years, % male: 87.5) - Ethnicity: Caucasian (3, 42.86 %), Chinese (1, 14.29 %) Latina and Caucasian (1, 14.29 %) Filipino and Caucasian (1, 14.29 %) Indian (1, 14.29 %)	–	Computer-based neuromodulation with neurofeedback for brain's mirroring system	–	Task performance, social skills, reported ASD symptoms, neural pattern	EEG	O
Selaskowski et al. (2023)	Germany	Posttest study	To develop and evaluate the first gaze-based attention-refocusing training in virtual reality for ADHD patients	ADHD: 18 (36.1 years, % male: 66.67) - Not reported	TD: 18 (25.9 years, % male: 61.11) - Not reported	VR-based neuromodulation with neurofeedback for cognitive skills	VR-based neuromodulation with neurofeedback for cognitive skills	Attention, ADHD symptoms, neural pattern	EEG	X
Chan et al. (2023)	Hong Kong	RCT	To investigate the effects of multisession cathodal prefrontal tDCS coupled with online cognitive remediation on social functioning, information processing efficiency, and the Excitation/Inhibition balance in ASD patients.	ASD: 30 (16.79 years, % male: 83.33) - Not reported	ASD: 30 (16.59 years, % male: 86.67 %) - Not reported	Mobile app-based neuromodulation with cathodal tDCS for social skills and cognitive skills	Sham intervention	Social skills, Information processing efficiency, neural pattern	EEG	O

(*continued on next page*)

Table 1 (continued)

	Country	Study design	Purpose	Sample: N (mean years, %male) - Races/ethnicity		Intervention		Outcomes	Measurement related to brain	Main findings
				Experimental	Control	Experimental	Control			
Peng and Leong (2024)	Malaysia	Pretest-posttest study	To explore the impact of different geometric styles on brain wave responses in autistic children during artistic creation and evaluate their potential effects on cognitive functioning and mental health.	ASD: 30 (7–14 years) - Not reported	–	VR-based cognitive training (art therapy) for cognitive skills and mental health	–	Cognitive skills, Mental health, neural pattern	EEG	O
Prillinger et al. (2024)	Austria	RCT	To investigate the effects of tDCS combined with a newly developed intrastimulation social cognition training on adolescents with ASD	ASD: 11 (14 years, % male: 100) - Not reported	ASD: 11 (14.27 years, % male: 100) - Not reported	Computer-based neuromodulation with anodal tDCS for social skills	Sham intervention	Emotional recognition, reported ASD symptoms, brain activity	fMRI	O
Bilan et al. (2025)	Spain	RCT	To assess the efficacy of the SincrolabDCT (KAD_SCL_01) on inhibitory control in pediatric ADHD-C	ADHD-C: 20 (9.41 years, % male: 80) - Not reported	ADHD-C: 21 (9.38 years, % male: 90.48) - Not reported	Mobile app-based cognitive training for cognitive skills	Sham intervention	Attention, impulsiveness, intelligence level (working memory, processing speed)	MEG	O
Mandapati and Ranjan (2025)	India	Pretest-posttest study	To examine the effectiveness of VR-based Brainwave Entertainment (VWE) in improving learning in children with ADHD.	ADHD: 11 (8.15 years, % male: 90.9) - Not reported	–	VR-based neuromodulation with brainwave entertainment for cognitive skills	–	ADHD symptoms	EEG	O

O: Cases where measurements of brain neuroplasticity corresponded to outcome and were effective.
△: Cases where measurements of brain neuroplasticity and outcome did not correspond, or were partially effective.
X: Cases where the intervention were not effective.
[a] ADHD: attention deficit hyperactivity disorder.
[b] EEG: electroencephalography.
[c] RCT: randomized controlled trial.
[d] ASD: autism spectrum disorder.
[e] fMRI: functional magnetic resonance imaging.
[f] TD: typical development.
[g] BCI: brain computer interface.
[h] VR: virtual reality.
[i] CBT: cognitive behavioral therapy.
[j] MEG: magnetoencephalography.
[k] ID: intellectual disability.
[l] tDCS: transcranial direct-current stimulation.
[m] DS: Down syndrome.

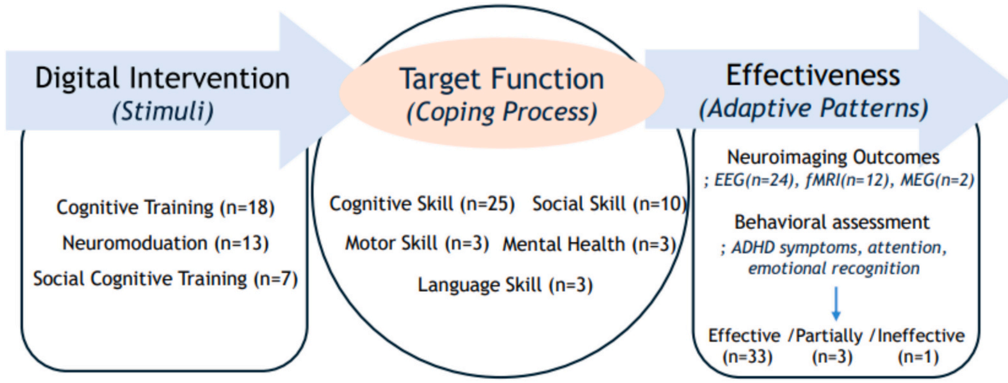

Fig. 2. Synthesis of the results according to the Roy's adaptation model.

et al., 2006, 2015). During the intervention, participants with ASD were exposed to 500 facial affect teaching items representing seven basic emotional states through educational text and comics (Bölte et al., 2006, 2015). Social cognitive training sessions lasted between 20 min to 2 h, with interventions spanning from 3 to 18 sessions. These interventions were administered to participants for 5 to 12 weeks.

3.3.2. Coping mechanisms

"Coping mechanisms" in RAM define how individuals manage internal and external stimuli (Roy and Andrews, 1999). This review adopted the targeted neural functions of the digital interventions as the concept of "coping mechanisms." Across the included studies, the most common target was cognitive skills (n = 19), followed by social skills (n = 9), and language skills (n = 3). In addition, two studies targeted both cognitive and motor skills, two targeted cognitive skills and mental health outcomes, and one study simultaneously targeted cognitive and social skills (Chan et al., 2023). One study targeted all three domains—cognitive skills, mental health, and motor skills—within a single intervention (De Luca et al., 2021).

Among the studies targeting cognitive abilities, the majority focused on enhancing attention (n = 15), followed by inhibitory control (n = 4) and working memory (n = 4) as representative domains. The interventions sought to improve cognitive skills that are often deficient in individuals with ADHD, ultimately aiming to alleviate ADHD symptoms.

Ten studies that aimed to enhance social skills focused on improving facial affect recognition and social interaction skills and were conducted with individuals with ASD. In the realm of motor skills, abilities such as motor coordination and equilibrium have been observed. De Luca et al. (2021) aimed to enhance the equilibrium and motor coordination of individuals with ASD using VR therapy. In this study, participants engaged in games such as mole catching or apple finding in a VR environment, encouraging the movement of both arms (De Luca et al., 2021). Lopes et al. (2022) used VR therapy that targeted upper limb movement in individuals with Down syndrome by requiring them to touch balls that changed color on a screen.

Three studies targeted language skills in individuals with dyslexia. Junttila et al. (2023) implemented a mobile app-based language-learning game that used speech recognition technology. Participants articulated English words in a board game format and received stars as feedback from an automatic speech recognizer to incentivize precise pronunciation (Junttila et al., 2023). Koen et al. (2018) had participants play "FlashWord," a computerized language learning game. The game required participants to decide whether two letter strings presented simultaneously matched each other, or whether a specific letter sounded the same as the other (Koen et al., 2018).

Research identifying coping mechanisms within the domain of mental health focused on anxiety and general mental health conditions. De Luca et al. (2021) identified anxiety as the target function in individuals with ASD. In the study, breathing training based on CBT was integrated into the final stage of VR-based cognitive training, to mitigate anxiety symptoms in individuals with ASD (De Luca et al., 2021). Whitehead et al. (2022) provided neurofeedback therapy to individuals with ADHD using a mobile application. Through this application, participants received personalized neurofeedback protocols aimed at improving mental health (Whitehead et al., 2022).

3.3.3. Adaptive patterns

RAM states that individuals develop adaptive patterns through the coping process (Roy and Andrews, 1999). Researchers have interpreted indicators of intervention effectiveness as "adaptive patterns." This review analyzed the effectiveness of the included studies according to the outcomes from neuroimaging methods and behavioral assessments. Studies were classified as "effective" when the intervention led to improvements in behavioral outcomes and these changes corresponded with measurable neuroplastic changes observed through neuroimaging. "Partially effective" referred to cases where either behavioral or neuroplastic changes were observed, but not both, or when the correspondence between the two was unclear. Studies were considered "ineffective" when no meaningful changes were reported in either behavioral or neuroimaging outcomes. Interventions were effective in 89 % (n = 33), partially effective in 8 % (n = 3), and ineffective in 3 % (n = 1) of the studies.

When intervention effectiveness was examined by participant group, studies targeting individuals with ADHD (n = 19) showed a high rate of effectiveness, with 89 % (n = 17) rated as effective, 5 % (n = 1) as partially effective, and 5 % (n = 1) as ineffective. For ASD (n = 13), 85 % were rated effective (n = 11), while 15 % were partially effective (n = 2). All studies targeting other diagnostic groups—dyslexia (n = 3), developmental dyscalculia (n = 1), Down syndrome (n = 1), and intellectual disabilities (n = 1)—were rated as effective.

By intervention type, cognitive training (n = 18) showed the highest rate of effectiveness, with 94 % of studies rated as effective (n = 17). Social cognitive training (n = 7) demonstrated 71 % effectiveness (n = 5), while 29 % were partially effective (n = 2). For neuromodulation (n = 13), 92 % of studies were effective (n = 12) and 8 % were ineffective (n = 1). Although social cognitive interventions showed a slightly lower proportion of effectiveness, these comparisons are based on descriptive proportions and not on statistical meta-analysis, and should therefore be interpreted with caution.

In terms of neuroimaging methods, most of the included studies used EEG to assess neuroplasticity (n = 23), followed by fMRI (n = 11) and magnetoencephalography (MEG) (n = 2). One study employed both EEG and fMRI (Russell-Chapin et al., 2013). Most studies assessed neuroplasticity using EEG by examining spectral power changes in specific frequency bands such as theta, alpha, or beta, while two studies analyzed amplitude within regions of interest (Junttila et al., 2023; Russell-Chapin et al., 2013). In addition, two studies employed ERP components as outcome measures, and De Luca et al. (2021) assessed

Table 2
Characteristics of the individual interventions.

Author (year)	Intervention delivery method	Targeted function (category; specific function)	Contents	Dose	Brain-related outcomes
Kotwal et al. (1996)	Computer based	Cognitive skills; attention	"Captain's Log" Computer-based cognitive training; participants engaged in structured on-screen tasks that required them to respond right answers to 8 tasks (auditory discrimination/rhythm, auditory discrimination/tone, color discrimination/inhibition, scanning reaction/inhibition, scanning reaction time, stimulus reaction time).	35 sessions 3 months	(EEG; neural patterns) - Theta: ↓ → f/u ↓ - Beta: ↓ → f/u ↓ - Theta/beta ratio: ↑ → f/u = - Facial EMG[a]: ↓ → f/u ↑
Pop-Jordanova et al. (2005)	Computer based	Cognitive skills; attention	"Biograph/Procomp 2.0" Computer-based neuromodulation with neurofeedback; a neurofeedback that measures theta, beta, SMR[b], EMG after audio and visual feedback	40 sessions 5 months 50 min each session	(EEG; neural patterns) - Theta: ↓ - Beta: ↑ - Theta/beta ratio: ↓ - Excessive EEG[c] slowing in the superior cortex and in the midline central cortex
Bölte et al. (2006)	Computer based	Social skills; facial affect recognition	"FEFA (Frankfurt Test and Training of Facial Affect Recognition)" Computer-based social cognitive training; a computer program that incorporates 500 facial affect teaching items using the 7 fundamental affective states for judging affect in whole faces and eye regions	5 sessions 5 weeks 2 h each session	(fMRI; brain activity) - Fusiform gyrus: no change - Medial occipital gyrus right: ↑ - Superior parietal lobule: ↑
Winn et al. (2006)	Computer based	Language skills	"Virtual Puget Sound" Computer-based cognitive training; simulation program for learning; a story-driven simulation intervention centered around the adventures of a young orca shale named Luna who became separated from his pod in Puget Sound. Students were tasked with learning essential concepts in oceanography and orca biology to support Luna's care and guide him back to the open ocean. As a culminating task, students created a cartoon strip depicting Luna's story and presented it orally.	4 sessions per week (8sessions) 2 weeks 45 min	(fMRI; brain activity) - Right cerebellum, V5 area ↑
Johnstone et al. (2010)	Computer based	Cognitive skills; response inhibition and working memory	Computer-based cognitive training program of a go/no-go and a working memory task where users try to find hidden items	25 sessions 5 weeks 20 min each session	(EEG; neural patterns) - Delta, theta, alpha: ↓ - Beta: not significant - ERP[d]s: N1, N2 amplitude↑, P3 amplitude not significant
Kucian et al. (2011)	Computer based	Cognitive skills; mathematical reasoning	"Rescue Calcularis" Computer-based cognitive training where users solve different number line based problems	25 sessions 5 weeks 15 min each session	(fMRI; brain activity) - After training, frontal lobe areas including middle and superior frontal regions, left postcentral gyrus, left intraparietal sulcus, and left insula: ↓ - After training, decrease after training is stronger in dyscalculic children than control children. - After 5-weeks, parietal lobule bilaterally: ↑, the other regions: no significant change
Lee and An (2011)	Computer based	Cognitive skills; attention	Computer-based cognitive training; a multimedia Intervention Program where users solve various tasks related to attention	13 sessions 24 weeks 20 min each session	(EEG; neural patterns) - Theta: ↓
Lim et al. (2012)	Computer based	Cognitive skills; attention	"CogoLand" Computer-based cognitive training; a BCI[e]-based attention training game where users mentally control an avatar to solve tasks	24 sessions 8 weeks (additional once-monthly booster sessions for 3 months) 30 min each session	(EEG; neural patterns) - BCI ADHD[f] Severity measure mean (SD): ↑ 60.9 (81.0) → 96.9 (64.7) - Paired *t*-test: not significant
Russell-Chapin et al. (2013)	Computer based	Cognitive skills associated with DMN[g] function	Computer-based neuromodulation with neurofeedback; a SMR Neurofeedback that unfolds puzzles into pictures when the correct SMR amplitude is obtained	40 sessions 13 weeks and 1 day 20 min each session	(fMRI; brain activity) - Brain activation in DMN area more consolidated after neurofeedback (EEG; neural patterns) - Sensorimotor amplitude means significantly ↑

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Table 2 (*continued*)

Author (year)	Intervention delivery method	Targeted function (category; specific function)	Contents	Dose	Brain-related outcomes
Bölte et al. (2015)	Computer based	Social skills; facial affect recognition	"FAR Training (Frankfurt Training for Facial Affect Recognition)" Computer-based social cognitive training; an intervention that incorporates 500 facial affect teaching items based on the 7 fundamental affective states while using visual and auditory reinforcement	8 sessions 8 weeks 60 min each session	(fMRI; brain activity) - In fusiform gyrus, amygdala, temporal pole bilaterally, the medial Prefrontal cortex, left posterior superior temporal sulcus: ↑
Jiang and Johnstone (2015)	Computer based	Cognitive skills; working memory, impulse control, attention/relaxation	Computer-based neuromodulation with neurofeedback; a themed computer game based neurofeedback combined with cognitive training of 14 different working memory, impulse control, and state control sessions	25 sessions 15–20 min each session	(EEG; neural patterns) - Beta; P1, P3, P5 ↑/P2=/P4 ↓ - Alpha: P1, P2, P5 ↓/P3, P4 ↑ - Zen (average): P1=/P2, P3, P5↑/P4 ↓
Bekele et al. (2016)	VR[h]	Social skills; facial affect recognition	"MASI-VR (Multimodel Adaptive Social Interaction in VR)" VR-based social cognitive training; adaptive multimodal VR platform where users identify facial expressions via interaction with various characters	3–5 sessions 20–25 min each session	(EEG; neural patterns) - Theta alpha, beta, gamma: all the features: ↓
Chung et al. (2016)	Computer based	Social skills; facial affect recognition	"Poki-Poki" Computer-based social cognitive training; a prosocial online game-CBT[i] where users practice responding to social and emotional words via interaction with various characters	18 sessions 6 weeks 1 h each session	(fMRI; brain activity) - In response to emotional words: right temporal lobe, left superior parietal lobe, left superior temporal lobe ↑ - In response to facial emoticons: right cingulated gyrus, left medial frontal gyrus, left cerebellum, left fusiform gyrus, left insular and sublobar area ↑ - Correlations with brain activity in left fusiform gyrus (in game CBT) - Positive: with the changes in the correct identification rate of emoticons - Negative: with the changes in SCQ-I[j] scores
Koen et al. (2018)	Computer based	Language skills; fluency development	"FlashWord" Computer-based cognitive training; a computerized visual hemisphere-specific stimulation program that consists of letters and phonetics- related tasks	Differing intervention schedules 24 h in total	(fMRI; brain activity) - Area where activation map ↑ = (n: pre → post): left hemisphere = 4 → 6, right hemisphere 1 → 8 - Brain activation peak intensity=: (pre) 2.998 → (post) 2.8965 - The largest activation area: (pre) posterior cingulate → (post) fusiform gyrus
Qian et al. (2018)	Computer based	Cognitive skills; attention	"CogoLand" Computer-based cognitive training; a BCI-based attention training game where users mentally control an avatar to solve different tasks	24 sessions 8 weeks 30 min each session	(fMRI; brain activity) - Functional connectivity: within SVN[k], SVN with DAN[l] and other networks ↑ - Topology: nodal degree and clustering coefficient ↓, nodal closeness ↑ in SVN, ECN[m] and DMN - FD[n] and DVARS[o]: no effect
Yang et al. (2018)	VR	Social skills; facial affect recognition, theory of mind	VR-based social cognitive training where users practice social conversational skills via a virtual avatar	5 weeks 10 h in total	(fMRI; brain activity) - BOLD[p] signal after VR: ↑ in the left superior parietal lobule - Significantly positive correlation: ↑ theory-of-mind change ↑ in the right posterior superior temporal sulcus - Significantly negative correlation: ↑ emotion-recognition ↓ in the left inferior frontal gyrus/ventrolateral prefrontal cortex
Georgiou et al. (2019)	VR	Cognitive skills; delay aversion, inhibitory control, attention, working memory Motor skills; motor coordination	"REEFOCUS game" VR-based cognitive training; a game-based intervention program where users maintain attention levels to complete tasks via two game modes: a virtual world mode and a multisensory mixed reality mode	16 sessions 8 weeks	(EEG; neural patterns) - Attention level: ↑, theta/beta ratio: ↓
Pereira et al. (2019)	Computer based	Cognitive skills related behavior problems	Computer-based neuromodulation with neurofeedback; a neurofeedback based on real-time fMRI[q] that uses visual contingent	2 sessions, each session 4 training runs 2 days	(fMRI; brain activity)

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Table 2 (*continued*)

Author (year)	Intervention delivery method	Targeted function (category; specific function)	Contents	Dose	Brain-related outcomes
			feedback while users recognize faces and emotions from different facial expressions		- The left Fusiform gyrus, left lingual cortex, and left inferior frontal gyrus: ↓ - Bilateral cerebellum: ↑
Meyer et al. (2020)	Computer based	Cognitive skills; inhibitory control	"Adaptive IC[r] training" Computer-based cognitive training; computer based go/stop games, consisting of 3 different baseball, fishing, and catapult games	20 sessions 4 weeks 15 min each session	(EEG; neural patterns) - Theta: ↓ - ERP latency of N200: ↑ longer
Rosenblau et al. (2020)	Computer based	Social skills	"Computer-based social-cognitive training (SCOTT)" Computer-based social cognitive training; a program that trains users in facial affect via social interaction of various actors and 24 games that require computation, visual discrimination, and attention to detail	3 months	(fMRI; brain activity) - Cortical thickness: ↑ in middle frontal gyrus - ↑ social-cognitive improvements, ↑ cortical thickness changes in anteriorly from the supramarginal gyrus, middle frontal gyrus
Chrisilla et al. (2021)	VR	Social skills	VR-based social cognitive training; VR environments where users learn days of the week and perform activities of daily living by familiarizing themselves with objects they use regularly	2 min each session	(EEG; brain activity) - Granger causality: higher than the normal children
De Luca et al. (2021)	VR	Cognitive skills; attention, working memory, spatial cognition Motor skills; equilibrium, motor coordination Mental health; anxiety	"BTS NIRVANA (BTSN)" VR-based cognitive training; semi-immersive VR environment with audio and visual stimuli where users interact with various scenarios to stimulate motor and cognitive domains along with relaxation exercises to reduce anxiety	3 sessions per week 8 weeks 30–45 min each session	(EEG; neural patterns) - Theta wave: ↓ - Alpha wave: ↓
Gallen et al. (2021)	Mobile app	Cognitive skills; attention	"AKL-T01 intervention" Mobile app-based cognitive training; a game-based digital therapeutics of a go/no-go task and a sensory motor navigation task where users adjust their location to interact with positional targets	5 sessions per week, 4 weeks; 25 min each session	(EEG; neural patterns) - Midline frontal theta: ↑
Medina et al. (2021)	Computer based	Cognitive skills; attention	"Digital Artificial Intelligence-Driven Intervention: KAD_SCL_01 games" Computer-based cognitive training; a digital game software with integrated AI[s] engine with 14 different puzzle, numerical, memory, identification games with visual and auditory stimuli	36 sessions 3 months 15–20 min each session	(MEG[t]; neural patterns) - Significant cluster in the posterior regions of the brain - MEG power ratio: ↑ - Continuous performance test commission ratio: ↓
Bluschke et al. (2022)	Computer based	Cognitive skills	"Different Theta and Beta Neurofeedback Training" Computer-based neuromodulation with neurofeedback; a neurofeedback of attention training where users move a character on screen	16 sessions 2 months 1 h each session	(EEG; neural patterns) - Theta: ↓ - Beta: ↑
Ha et al. (2022)	Mobile app	Cognitive skills; attention	"Do Brain App: Mobile app-based digital intervention" Mobile app-based cognitive training; do Brain App with 108 story and game sessions to train cognition	3 times per week (2 story sessions & 1 game session per day) 12 weeks	(EEG; neural patterns) Eyes closed condition - Theta power: ↑ (frontal region), ↓ (left frontal channels), ↑ (one frontal channel) - Theta/beta ratio: ↓ (one central channel) Eyes open condition - Theta power: ↓ - Alpha power: ↓ - Beta power: ↑ (one left temporal channel) - Theta/beta ratio: ↓
Lopes et al. (2022)	VR	Cognitive and motor skills associated with reorganization of brain impulses	"Neuromodulation with anodal tDCS[u] combined with VR training" VR-based neuromodulation with anodal tDCS; a neuromodulation with VR training where users touch the ball that changes its color	10 sessions 3 times per week on nonconsecutive days 20 min each session	(EEG; neural patterns) - Alpha ERD[v]/ERS[w] curve: ↓ - Beta ERD/ERS curve: ↓ - Cerebral cortex map: change in alpha and beta synchronization, and alpha and beta desynchronization
Luo et al. (2023)	Mobile app	Cognitive skills; attention, working memory, inhibitory control	"Focus Pocus" Mobile-app based cognitive training and neuromodulation with neurofeedback; a training program with 14 neurofeedback	3–5 training sessions per week 3 months	(EEG; neural patterns) - Theta: no change - Alpha: ↑

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Table 2 (*continued*)

Author (year)	Intervention delivery method	Targeted function (category; specific function)	Contents	Dose	Brain-related outcomes
			and cognitive training games based on go/no-go and working memory tasks		- Beta: no change - Theta/beta ratio: no significant effect
Whitehead et al. (2022)	Mobile app	Cognitive skills and mental health	"Myndlift: App-based remote Neurofeedback Therapy" Mobile app-based neuromodulation with neurofeedback; a neurofeedback therapy that delivers visual and auditory feedback while users train via YouTube videos and games	20 or more sessions 30–180 days	(EEG; neural patterns) - Delta/alpha ratio: ↓ - Theta/alpha ratio: no change - Theta/beta ratio: no change
Junttila et al. (2023)	Mobile app	Language skill	"Say it again, kid" (SIAK): language-learning game" Mobile app-based cognitive training; a language learning program of word imitation tasks where users say words aloud and receive feedback from an automatic speech recognizer	1 session per day 2.8 days a week 5 weeks 16.3 min each session	(EEG; neural patterns) - Mismatch negativity amplitude: ↑
LaMarca et al. (2023)	Computer based	Social skills associated with the brain's mirroring system	"Neurofeedback training of mu rhythms" Computer-based neuromodulation with neurofeedback; a neurofeedback that changes or stops visual content when the EEG threshold criteria were met while users watched movies	2 sessions per week 20 weeks 45 min each session	(EEG; neural patterns) - Mu suppression: ↑
Selaskowski et al. (2023)	VR	Cognitive skills; attention	"Gaze-based attention training using VR" VR-based neuromodulation with neurofeedback; a gaze-based attention training where users perform a Continuous Performance Task (CPT) amid distracting events with audiovisual feedback	2 days; 4 h in total	(EEG; neural patterns) - Time-frequency power spectra: no effect - Theta/beta ratio: distracting phase > non-distracting phase
Chan et al. (2023)	Mobile app	Cognitive skills; information processing efficiency Social skills Social functioning	"Prefrontal tDCS with cognitive training" Mobile app-based neuromodulation with cathodal tDCS; a tDCS session administered during cognitive game (Lumosity®), comprising 10 game-based tasks targeting executive domains; including games requiring interference control (e.g., filtering distracting stimuli), working memory (e.g., recalling visual sequences), set shifting (e.g., switching rules based on stimulus features), multitasking, and rapid visual processing.	5 sessions per week (10 sessions) 2 weeks 20 min each session	(EEG; neural patterns) - Theta band E/I ratio[x], gamma band E/I ratio - Theta band E/I ratio: ↓ (midline) - Gamma band E/I ratio: ↓ (not significant)
Peng and Leong (2024)	VR	Cognitive skills, mental health	VR-based cognitive training; an art therapy conducted in an immersive virtual environment using head-mounted displays and EEG monitoring. Participants created artworks composed of geometric elements such as straight lines, rectangles, and color blocks.	1 session per week (3 sessions) 3 weeks 30 min	(EEG; neural patterns) - Alpha: ↑
Prillinger et al. (2024)	Computer based	Social skills; facial affect recognition	"Anodal tDCS and intrastimulation training" Computer based neuromodulation with anodal tDCS; a standardized procedure that presents different stimuli in each session; a 5-min movie segment showed an animated movie about emotions and asked questions about Theory of Mind and emotion recognition abilities to the participants; the next segment comprised three distinct emotion recognition tasks, "Face Emotion," "Social Scenes," and "Morphing," and instructed participants to watch videos of actors expressing emotions and select correct emotion label.	10 sessions 2 weeks 20 min per session	(fMRI; brain activity) - Across the DMN: ↓ - (In the social brain network) intraparietal sulcus, inferior frontal sulcus, cingulate sulcus, and (emotional processing) posterior hippocampus: ↑ - Visual network (fusiform area): ↑
Bilan et al. (2025)	Mobile app	Cognitive skills; attention, inhibitory control	"SincrolabDCT (KAD_SCL_01)" Mobile app-based cognitive training; a serious game consisted of 14 cognitive games designed and developed based on scientifically supported neuropsychological tasks (e.g., go/no-go task, n-back task).	3 sessions per week; 12 weeks; 15 mins per session	- Correlation at specific brain regions (temporal, precuneus, angular gyrus) and specific bands (alpha, beta): ↑
Mandapati and Ranjan (2025)	VR	Cognitive skills; attention, spatial learning	VR based neuromodulation with brainwave entertainment; participants experienced 10 Hz visual pulses (white light) embedded in 360° VR videos of birds and animals, combined with 10 Hz binaural beats delivered via earphones.	1 session per day (20 sessions) 20 days 15 min	(EEG; neural patterns) - Theta: ↓ (n = 7/11) - Alpha: ↓ (n = 6/11) - Beta: ↑ (n = 7/11) - TBR: ↓ (n = 6/11)

[a] SMR: sensory motor rhythm.
[b] EMG: electromyography.
[c] EEG: electroencephalography.
[d] ERP: event-related potential.
[e] BCI: brain-computer interface.
[f] ADHD: attention deficit hyperactivity disorder.
[g] DMN: default mode network.
[h] VR: virtual reality.
[i] CBT: cognitive behavioral therapy.
[j] SCQ-I: social communication questionnaire current form, Korean version - reciprocal social interaction.
[k] SVN: salience/ventral attention network.
[l] DAN: dorsal attention.
[m] ECN: executive control network.
[n] FD: frame displacement.
[o] DVARS: rate of change of BOLD signal across the entire brain.
[p] BOLD: blood oxygenation level-dependent.
[q] fMRI: functional magnetic resonance imaging.
[r] IC: inhibitory control.
[s] AI: artificial intelligence.
[t] MEG: magnetoencephalography.
[u] tDCS: transcranial direct-current stimulation.
[v] ERD: event-related desynchronization.
[w] ERS: event-related synchronization.
[x] E/I ratio: excitement/inhibition ratio.

functional connectivity using EEG. Other approaches included calculating attention levels based on EEG features (Georgiou et al., 2019) and deriving ADHD severity scores using EEG-based algorithms (Lim et al., 2012).

In the subset of studies focusing on spectral power analysis, the predominant waves measured were theta (n = 12), beta (n = 9), alpha (n = 7), and theta/beta ratio (n = 8). In 8 out of 12 studies, theta waves decreased following the intervention. Five studies reported an increase in beta waves, two showed no difference, and two indicated a decrease. Of the seven studies measuring alpha waves, five reported a decrease, and four of the seven studies measuring theta/beta ratio also reported a decrease.

Of the articles that utilized fMRI to assess participants' neuroplasticity, five studies observed blood oxygenation level-dependent (BOLD) signals to ascertain the impact of the intervention on neuroplasticity. Most studies revealed a notable trend of increased BOLD signal following the intervention (n = 4).

In addition, the reviewed studies employed various behavioral assessment methods to evaluate the effectiveness of the interventions, including ADHD symptoms (n = 14), attention (n = 6), emotional recognition (n = 5), and social skills (n = 5). Additionally, three studies examined behavioral problems, while two studies included executive function and response inhibition.

ADHD symptoms were evaluated utilizing assessment tools such as the ADHD Rating Scale. Except for Selaskowski et al. (2023), studies measuring ADHD symptoms indicated that digital interventions were effective in alleviating ADHD symptoms. Attention was assessed through methods such as the Continuous Performance Task (CPT) that evaluates participants' attention level using their reaction time and error rates. Five of the six studies (except Selaskowski et al.) reported an improvement in attention following the interventions.

Emotion recognition was assessed using instruments such as the Frankfurt Test for Facial Affect Recognition test, Emotion Recognition Test, and Advanced Clinical Solutions-Social Perception subtest. These instruments assigned facial emotion recognition tasks and evaluated the performances. Positive outcomes were evident in all studies that assessed emotion recognition. Social skills as an outcome were assessed using the Social Communication Questionnaire (SCQ), the Conners Parent Rating Scale, and Movie for the Assessment of Social Cognition (MASC). The Conners Parent Rating Scale and SCQ were survey-based measurement tools where parents or participants assessed social skills. For MASC, participants were presented with specific tasks while watching movies depicting social situations. Subsequently, trained evaluators assessed social skills by observing their performance. The social skills were enhanced across all these studies.

4. Discussion

This review consolidated findings from 37 peer-reviewed published studies, assessing the impact of digital interventions on neuroplasticity and brain functionality in individuals with DDs. A strength of this review was its theoretical basis on an established conceptual framework, RAM. This theoretical underpinning facilitated a systematic approach to categorizing digital interventions (as stimuli), targeted brain functions (as coping mechanisms), and outcomes of these interventions (as adaptive patterns).

The current study clarified the effectiveness of digital interventions on the neurological functions of individuals with DDs. Of the 37 reviewed studies, 33 reported positive outcomes in at least one neurological function. The current results are consistent with those of previous reviews that reported positive possibilities of the integration of digital technologies into various interventions, training, or programs for individuals with DDs (Burns et al., 2019; Torra Moreno et al., 2021).

In this review, only Selaskowski et al. (2023) did not report significant improvements in children with ADHD. The researchers provided audio-visual feedback based on eye movements to increase self-awareness of eye movements and alleviate ADHD symptoms. However, individuals with ADHD perceived the feedback as a distraction due to their susceptibility to external stimuli, leading to a worsening of ADHD symptoms. They also observed that a single-session intervention was inadequate to address cognitive skills. Although the effectiveness of digital interventions is highly plausible, it is critical to consider various characteristics of DDs that may be suitable for the features of digital interventions. This is further supported by Jiang and Johnstone (2015), who reported unintended changes in EEG waves. The researchers attributed the cause of these changes to a failure in difficulty adjustment because individuals with ADHD can improve their cognitive abilities by practicing at an appropriate level of difficulty, which facilitates achievement.

This review identified three main intervention types used by included studies to enhance the neural functioning of individuals with DDs: cognitive training, neuromodulation, and social cognitive training. These interventions were integrated with digital devices, showing a trend of moving from computer-based to tablet or mobile-based approaches. Specifically, the current findings demonstrated that most of the reviewed studies utilized cognitive training interventions targeting the "attention" of individuals with ADHD. While there were individuals with other types of DDs, such as ASD or Down syndrome, studies focusing on populations with ADHD and their often-reported cognitive deficiencies predominated this review. Digital interventions aimed at individuals with intellectual disabilities also report the effectiveness of these interventions at improving the participants' cognitive or behavioral functions (Burns et al., 2019; Torra Moreno et al., 2021). Further research concerning populations with different DDs and interventions that integrate emerging digital technologies to enhance brain function is essential.

In addition, it would be beneficial to explore the diverse content of interventions that can be integrated into digital platforms, particularly those that can enhance neuroplasticity. Cognitive training, neuromodulation, and social cognitive training identified in this review required participants to remain sedentary while completing tasks aimed at enhancing neuroplasticity. However, researchers suggest various approaches, such as movement therapy (e.g., exercise), to enhance neuroplasticity in individuals with DDs (Oh et al., 2024; Su et al., 2022; Vogt et al., 2013). This review included studies that conducted digital interventions to enhance the neural functions of individuals with DDs and evaluated the effects of these interventions using neuroimaging methods. This might be why studies using various interventions (e.g., movement therapy for neuroplasticity of individuals with DDs, but not integrated in digital devices) were excluded. Future studies should evaluate the effects of various intervention contents that integrate digital technologies.

Furthermore, our findings indicate that only two studies utilizing CBT were based on a defined theoretical framework (Chung et al., 2016; De Luca et al., 2021). There is a concern among researchers that many digital interventions lack a solid theoretical basis, leading to insufficient justification for their use (Taj et al., 2019). Researchers should design digital interventions that are grounded in well-established theoretical frameworks.

In terms of the neuroimaging methods identified in this review, EEG and fMRI were predominantly utilized to elucidate the changes in the brains of individuals with DDs. Of the 24 studies that analyzed EEG, 16 targeted individuals with ADHD. There was a consistent trend indicating a decrease in theta waves and theta/beta ratio, which could be interpreted as normalization of characteristic abnormal brain wave patterns seen in individuals with ADHD. This is because individuals with ADHD typically exhibit higher theta band activity and theta/beta ratio compared to those without it (Loo and Makeig, 2012).

Of the 12 studies that analyzed fMRI data, seven targeted individuals with ASD, aiming to improve their social skills and emotional recognition abilities through interventions. The findings of these studies suggested an increase in indicators of brain activation such as the BOLD signal. The investigators identified activation in the "social brain" area, which is responsible for social cognition skills, particularly emotion recognition. The studies revealed an augmented activation in the social brain network associated with analysing faces and gaze, such as the fusiform gyrus and superior temporal sulcus. Additionally, areas associated with understanding the emotions and thoughts of others, such as the prefrontal cortex, exhibited increased activity (Müller and Fishman, 2018).

A comprehensive analysis of the neuroimaging results confirmed the possibility of mixed interpretations of the same findings. An increase in alpha waves in individuals with ADHD is generally considered a positive signal, and efforts are made to increase alpha waves. However, this review revealed a notable trend of decreased alpha waves following the intervention, leading to mixed interpretations of these results. Jiang and Johnstone (2015) and Bekele et al. (2016) argued that the intervention was not sufficiently effective for the participants, possibly due to failure in difficulty adjustment. Johnstone et al. (2010) and Ha et al. (2022) suggested that decreased alpha waves cannot simply be interpreted as a negative response, given that the researchers did not sufficiently account for the diverse subtypes of neurological characteristics of the participants. This indicates that due to the various neurological subtypes observed in individuals with ADHD, a universally consistent interpretation is not possible.

Furthermore, research on neuroimaging interpretation has not been extensively conducted, and neuroimaging is currently recognized as a supplementary factor in diagnosing and assessing ADHD and ASD (McPartland et al., 2021; Slater et al., 2022). Based on this review and recent research, it would be possible to propose considerations for neuroimaging interpretation when investigating the effects of interventions on neuroplasticity in individuals with DDs. First, it is essential to establish the correlation between neuroimaging findings and other behavioral assessments or clinical outcomes. Additionally, selecting participants with consistent neuroimaging-related subtypes across interventions can help eliminate additional variables that may influence neuroimaging results.

Finally, the included studies were concentrated in countries with well-developed information technology industries, such as the United States, Germany, and South Korea. This is supported by a systematic review examining the application of digital technology on behavior change and highlighting this geographic limitation (Loo and Makeig, 2012). Digital technology can provide efficiency, leading to greater impact in vulnerable areas, thus emphasizing the need to pay attention to digitally vulnerable regions (Zhang et al., 2023).

The MMAT-based quality assessment revealed that the majority of included studies demonstrated high methodological quality, with 16 studies achieving a perfect score and 33 scoring above 60 %. RCTs generally exhibited stronger methodological rigor due to their structured design. However, blinding emerged as a common limitation, likely due to the inherent characteristics of digital interventions, which often require active participant engagement through visible platforms (e.g., computer games, VR, or mobile apps). As participants are typically aware of the type of intervention they receive, implementing participant blinding becomes structurally challenging.

By contrast, non-RCT studies showed relatively weaker quality, particularly in controlling for confounders and ensuring representative sampling. These limitations were often associated with vague or absent inclusion criteria and the lack of a control group. Notably, the criterion concerning the appropriateness of outcome measurements was unmet only in those studies that received the lowest quality scores, highlighting the importance of using reliable and validated tools. These findings highlight the need for future research to enhance transparency in study design, strengthen confounder control, and ensure the validity of outcome measurements.

5. Limitations

This review had some limitations. It included only full-text and English-language publications. Unpublished and ongoing studies, guidelines, protocols, qualitative studies, and non-English publications were excluded. Consequently, this may limit the interpretation of the findings. Additionally, this review did not conduct a meta-analysis; therefore, it was not possible to determine the magnitude of effect or to statistically compare the effectiveness of digital interventions across different participant groups or intervention types. This was primarily owing to the considerable heterogeneity in outcome measures, evaluation methods, and the digital intervention protocols used across studies. Despite these limitations, it provided insights into the application of digital interventions on individuals with DDs and allowed identification of their effects on neuroplasticity.

6. Conclusions

This review highlighted the promising potential of digital interventions integrated with cognitive training, neuromodulation, and social cognitive training to improve neural functions and neuroplasticity in individuals with DDs. The interventions showed significant improvements. The positive outcomes have been proven through a reduction in abnormal brain wave patterns, increased activation in regions associated with social cognition, and positively influenced behavioral outcomes. Yet, additional studies including a broader spectrum of DDs and more diverse methodological frameworks are warranted to fully understand the effectiveness of digital interventions targeting neurodevelopmental challenges of the population.

Glossary

Developmental disabilities A group of chronic conditions that originate in childhood and affect cognitive, physical, language, behavioral, and self-care functions

Neuroplasticity The brain's ability to reorganize itself structurally and functionally in response to internal and external stimuli such as learning, experience, or injury

Electroencephalography (EEG) A neurophysiological method that records electrical activity of the brain via scalp electrodes

Functional magnetic resonance imaging (fMRI) A neuroimaging technique that measures brain activity by detecting changes in blood oxygenation and flow

Event-related potentials (ERPs) Brain responses measured by EEG that are time-locked to specific sensory, cognitive, or motor events

BOLD signal Blood-oxygen-level-dependent signal used in fMRI to measure brain activity based on changes in blood flow

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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