ACCSCIENCE PUBLISHING

Advanced Neurology

REVIEW ARTICLE

Virtual reality interventions targeting executive functions across neurological, neurodevelopmental, neuropsychiatric, and non-clinical populations: A systematic review

Nikolaos Drakatos[1,2]*, Pantelis Pergantis[1]*, Andreas Petropoulos[3,4], Nikolaos Bardis[2], Nikolaos Doukas[2], and Athanasios Drigas[1]*

[1]Net Media Lab & Mind & Brain R&D, Institute of Informatics & Telecommunications, National Centre of Scientific Research "Demokritos," Agia Paraskevi, Greece

[2]Hellenic Army Academy, Leoforos Eyelpidon (Varis – Koropiou) Avenue, Vari, Greece

[3]Unit of Developmental and Behavioral Pediatrics, First Department of Pediatrics, School of Medicine, National and Kapodistrian University of Athens, "Aghia Sophia" Children's Hospital, Athens, Greece

[4]Department of Physiotherapy, School of of Health Sciences, University of Thessaly, Lamia, Greece

***Corresponding authors:**
Nikolaos Drakatos (ngdrakatos@gmail.com);
Pantelis Pergantis (p.pergantis@iit.demokritos.gr);
Athanasios Drigas (dr@iit.demokritos.gr)

Citation: Drakatos N, Pergantis P, Petropoulos A, Bardis N, Doukas N, Drigas A. Virtual reality interventions targeting executive functions across neurological, neurodevelopmental, neuropsychiatric, and non-clinical populations: A systematic review. *Adv Neurol.* 2026;5(4):026290039. doi: 10.36922/AN026290039

Received: July 17, 2026

Revised: August 12, 2026

Accepted: August 18, 2026

Published online: August 27, 2026

Copyright: © 2026 Author(s). This is an Open-Access article distributed under the terms of the Creative Commons Attribution License, permitting distribution, and reproduction in any medium, provided the original work is properly cited.

Publisher's Note: AccScience Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Abstract

Virtual reality (VR) offers interactive environments that may support executive-function (EF) training. This systematic review examined the VR technologies used, their effects on EF outcomes, and the maintenance of effects across neurological, neurodevelopmental, neuropsychiatric, and non-clinical populations. Following PRISMA 2020, we searched Web of Science, PubMed, Scopus, and Google Scholar for peer-reviewed empirical studies published from January 1, 2015, to December 31, 2025. Eligible studies examined VR-based interventions targeting one or more EF domains. Fourteen studies met the inclusion criteria. Interventions ranged from non-immersive screen-based systems and telerehabilitation platforms to fully immersive head-mounted display systems. Common approaches included serious games, everyday-life simulations, adaptive difficulty, and performance feedback. The most consistent improvements were reported for inhibitory control, cognitive flexibility or shifting, and planning or problem solving. Findings for working memory or updating were more mixed. Studies using domain-specific EF measures, such as the Stroop test, Trail Making Test, and Tower of London, provided clearer evidence than studies relying mainly on global cognitive measures. Most studies assessed outcomes only immediately after intervention, and few included follow-up assessments. VR-based interventions show promise for improving selected executive processes across clinical and non-clinical populations, but effects vary by population, intervention design, and outcome measure. Longer follow-up, standardized EF measures, and functional outcomes are needed to clarify the durability and clinical relevance of these effects.

Keywords: Virtual reality; Executive functions; Cognitive training; Inhibition; Cognitive flexibility; Working memory

1. Introduction

Executive functions (EF) are complex cognitive processes that help individuals control their behavior, adapt to new situations, and achieve goals. The key EF skills include working memory, inhibitory control, and cognitive flexibility. More advanced executive tasks involve planning, reasoning, and solving problems.[1] Difficulties with EF can affect anyone at any age and are common in neurological and neurodevelopmental conditions such as traumatic brain injury (TBI), dementia, stroke, Parkinson's disease, attention-deficit/hyperactivity disorder (ADHD), and mild cognitive impairment (MCI). These challenges can decrease quality of life, hinder independence in daily activities, and increase the burden on caregivers.[2-4]

Traditional EF rehabilitation methods, such as paper-and-pencil tasks and standard computer programs, can produce measurable improvements; however, they often face limitations such as low ecological validity, inconsistent transfer to daily activities, and declining engagement or motivation over time.[5] Virtual reality (VR) has gained popularity as a supplementary approach because it offers interactive, controllable environments where individuals can practice realistic tasks under consistent conditions, frequently with immediate feedback and varying difficulty levels.[4,6]

Virtual reality is increasingly used in health and cognitive applications because it can simulate everyday environments with controllable task demands and real-time feedback. For EF, VR may enhance ecological validity by embedding inhibition, shifting, working memory, and planning demands within goal-directed activities resembling real-world contexts.[7-9]

Executive functions support self-regulation of cognition and behavior and contribute to learning performance and well-being across development. In childhood and adolescence, EF skills predict educational outcomes and are associated with longer-term indicators in adulthood.[2,10,11] EF domains are commonly assessed using standardized neuropsychological measures; for example, cognitive flexibility is often evaluated with tasks such as the Wisconsin Card Sorting Test, working memory using digit span measures, and inhibitory control with paradigms such as the Stroop test.[1,12,13] Because EF components are interrelated, impairment in one domain can disrupt broader executive control, including planning, organization, problem solving, and processing efficiency.[14]

Virtual reality is typically conceptualized as a technology that enables real-time computer-generated environments that users can experience and interact with in ways that approximate real-world contexts.[15] Over the past decade, advances in hardware and software have increased the accessibility and affordability of VR, accelerating its use in research and clinical applications.[16] VR can be broadly defined as a computer-generated simulation of a real or imagined three-dimensional environment that allows users to interact with events in ways that emulate real-life conditions.[17] Compared with traditional cognitive training, VR can deliver structured, controllable tasks, support data capture, and provide real-time performance feedback.[18] VR systems are commonly categorized by immersion level as non-immersive, semi-immersive, or fully immersive (head-mounted display [HMD]–based) formats[19–23], and these configurations may differ in usability, tolerability, and the degree to which training approximates everyday executive demands.

Although EF can improve with structured practice, executive performance is also sensitive to stressors and shaped by environmental and neurological influences.[12] Executive control is therefore likely to benefit most from interventions that combine adequate intensity with tasks that meaningfully engage core EF processes (e.g., updating, inhibition, and switching) and promote generalization beyond trained activities. For example, the capacity to update working memory supports advanced skills such as planning, goal maintenance, logical reasoning, and managing dual tasks.[1] The involvement of core EF processes across a range of higher-order cognitive skills suggests that interventions targeting EF domains could yield wide-ranging, functional benefits.

Two previous systematic reviews provide important but distinct foundations for the present work. Borgnis *et al.*[24] broadly mapped VR-based tools developed for both the assessment and rehabilitation of EF across healthy and clinical populations. Kirkham *et al.*[25] focused more specifically on immersive HMD-based methods for assessing EF in adults, emphasizing construct validation, immersion, user experience, and cybersickness. The present review differs from and extends these earlier syntheses by focusing specifically on empirical VR-based intervention and training studies rather than assessment-only applications, including non-immersive, semi-immersive, and fully immersive systems, and synthesizing outcomes across specific EF domains and diverse populations. It also updates the intervention evidence through December 31, 2025, and explicitly examines intervention duration and the maintenance of effects at follow-up.[24-26]

The present review, conducted in line with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines, systematically examines the evidence on how VR impacts EF. It includes studies published from January 1, 2015, to December 31,

2025, identified through searches in PubMed, Web of Science, Scopus, and Google Scholar, along with backward and forward citation searches. After applying specific inclusion and exclusion criteria, 14 studies were selected from 457 records, allowing for a focused synthesis of the eligible empirical evidence.

Accordingly, the objective of this systematic review was to synthesize empirical evidence on VR-based interventions targeting EF across neurological, neurodevelopmental, neuropsychiatric, and non-clinical populations. Specifically, the review examined: (i) the VR technologies and intervention approaches used to target EF; (ii) their effects on EF outcomes; and (iii) the duration and maintenance of any observed effects.

2. Methods

2.1. Study design

Following the PRISMA guidelines for systematic reviews and meta-analyses, this review adopted a systematic review design to identify, select, evaluate, and synthesize relevant literature. The review protocol was registered on the Open Science Framework (https://osf.io/ecnfz/) on April 16, 2025. This systematic review addresses the following research questions for the final set of included studies.

(i) RQ1. Which VR technologies and intervention approaches have been used to target EF across the eligible populations?
(ii) RQ2. What effects have VR-based interventions demonstrated across specific EF domains?
(iii) RQ3. To what extent were the observed effects maintained after completion of the intervention?

2.2. Inclusion and exclusion criteria

Based on our objective and research questions, the following inclusion and exclusion criteria were used in this systematic review.

Studies were included if they met all of the following criteria:

(i) Published between January 1, 2015, and December 31, 2025.
(ii) Original empirical research using quantitative, qualitative, or mixed methods designs that reported eligible pre–post and/or controlled EF-related outcome data.
(iii) Investigated VR-based interventions/training intended to enhance EF and reported EF-related outcomes (e.g., inhibition, working memory, cognitive flexibility, planning, attentional control).
(iv) Included participants with neurological, neurodevelopmental, or neuropsychiatric conditions, and/or non-clinical participants, provided that the study evaluated a VR-based intervention targeting one or more EF domains.
(v) Published as a peer-reviewed journal article.
(vi) Written in English.
(vii) Full text was available for screening and data extraction.

For the purposes of this review, neurological populations included participants with conditions such as stroke, TBI, Parkinson's disease, MCI, and multiple sclerosis (MS). Neurodevelopmental populations included participants with ADHD, while neuropsychiatric populations included individuals with schizophrenia- or psychosis-spectrum disorders. Non-clinical populations included healthy adults, healthy older adults, community-dwelling older adults without a specific clinical diagnosis, and general population samples.

Studies were excluded if they met any of the following criteria:

(i) Published before 2015.
(ii) Systematic reviews, meta-analyses, and narrative/literature reviews.
(iii) Did not include a VR component (e.g., conventional therapy alone, standard computerized training).
(iv) Did not assess or report outcomes related to EF or EF domains.
(v) Excluded studies using VR only for EF assessment/measurement (i.e., no intervention/training component).
(vi) Not written in English.
(vii) Full text was not accessible (restricted access preventing screening/data extraction).

These eligibility criteria were selected to align with the review objectives and its focus on VR applications targeting EF. For this review, VR was defined broadly to include fully immersive, semi-immersive, and desktop-based VR systems that provide interactive, computer-generated environments designed to promote cognitive engagement. Studies that did not involve VR, as defined, were excluded. The included studies, therefore, covered the full continuum of immersion, from HMDs to "desktop-based" VR applications. The 2015–2025 publication restriction applied only to studies considered for inclusion; background references cited elsewhere in the manuscript were not restricted by publication year.

2.3. Databases screened and selection process

A comprehensive literature search was conducted across Web of Science, PubMed, and Scopus, with additional searching in Google Scholar. The search strategy followed PRISMA 2020 guidance and aimed to identify peer-

reviewed empirical studies examining VR applications targeting EF. To maximize coverage, database searching was supplemented by backward and forward citation chasing (snowballing) from included studies and closely related papers.

Search terms were organized into two concept blocks: (i) VR-related terms and (ii) EF-related terms. Synonyms and related terms within each block were combined using the Boolean operator OR, while the two concept blocks were combined using AND. The central search terms are presented in Table 1, and the complete database-specific search strategies are provided in the Appendix.

Study selection proceeded in two stages. First, titles and abstracts were screened against predefined eligibility criteria, resulting in 72 exclusions and 59 reports retained for full-text assessment. Second, full texts were assessed for eligibility; 45 reports were excluded with documented reasons (full text not accessible [n = 11]; no/insufficient VR component [n = 14]; outcomes not assessing EF [n = 9]; EF assessment only/no VR intervention [n = 4]; no eligible pre–post/controlled outcome data [n = 3]; non-English [n = 4]). The final set included 14 studies, which were subsequently included in the qualitative synthesis and results mapping to the review research questions.

Title and abstract screening and full-text eligibility assessment were performed independently by two reviewers (N.Dr and P.P). The reviewers compared their decisions after each screening stage, and any disagreements were resolved through discussion and consensus. When agreement could not be reached, a third reviewer (A.P) reviewed the article and made the final decision.

A systematic literature search was conducted across four platforms to identify studies examining the effects of VR interventions on EF and related domains. Searches combined controlled vocabulary, where available, and free-text terms representing two concepts: (i) VR and related technologies and (ii) EF and its principal domains. Terms within each concept were combined with OR, and the two concepts were combined with AND. The final searches were conducted on January 12, 2026, and were restricted to English-language journal articles published between January 1, 2015, and December 31, 2025. Complete reproducible search strategies, including database-specific fields, limits, and filters, are provided in the Appendix.

2.4. Data extraction

Data were extracted independently by two reviewers (N.Dr and P.P) using a standardized extraction form developed for this review. Extracted information included participant characteristics (sample size, age, sex, and clinical status); study metadata (authors, year, and country); and methodological characteristics (study design, comparison conditions, intervention features, and outcome measures). Data concerning VR technology and immersion level, intervention type, targeted EF domains, principal EF-related findings, intervention duration, and follow-up timing were also recorded.

The two reviewers compared the completed extraction forms, and discrepancies were resolved through discussion and consensus. Where agreement could not initially be reached, a third reviewer (A.P) reviewed the original article and adjudicated the final extraction decision.

2.5. Included studies

Following database searching and study selection in accordance with PRISMA 2020, 457 records were identified between January 1, 2015, and December 31, 2025 (Web of Science [n = 124], PubMed [n = 123], Scopus [n = 116], and Google Scholar [n = 94]). After removing 326 duplicates, 131 unique records remained for screening. Titles and abstracts were screened against the predefined eligibility criteria, and 72 records were excluded for failing to meet inclusion requirements (e.g., not VR-based, not EF-related, non-empirical). The remaining 59 reports were retrieved and assessed in full text for eligibility.

Of the 59 full-text articles assessed, 45 were excluded with documented reasons: full text not accessible (n = 11), no/insufficient VR component according to the operational definition (n = 14), outcomes did not assess EF (n = 9), EF assessment only (no VR intervention/training) (n = 4), no eligible pre–post/controlled outcome data (n = 3), and non-English (n = 4). The final synthesis, therefore, included 14 studies that met all inclusion criteria (Figure 1).

Table 1. Central search strings

Concept block	Search terms
Virtual reality	"virtual reality" OR VR OR "immersive virtual reality" OR "virtual environment" OR "head-mounted display" OR HMD OR "360 video" OR "serious game"
Executive functions	"executive function" OR "inhibitory control" OR "working memory" OR planning OR "attentional control" OR "problem solving" OR "cognitive control"

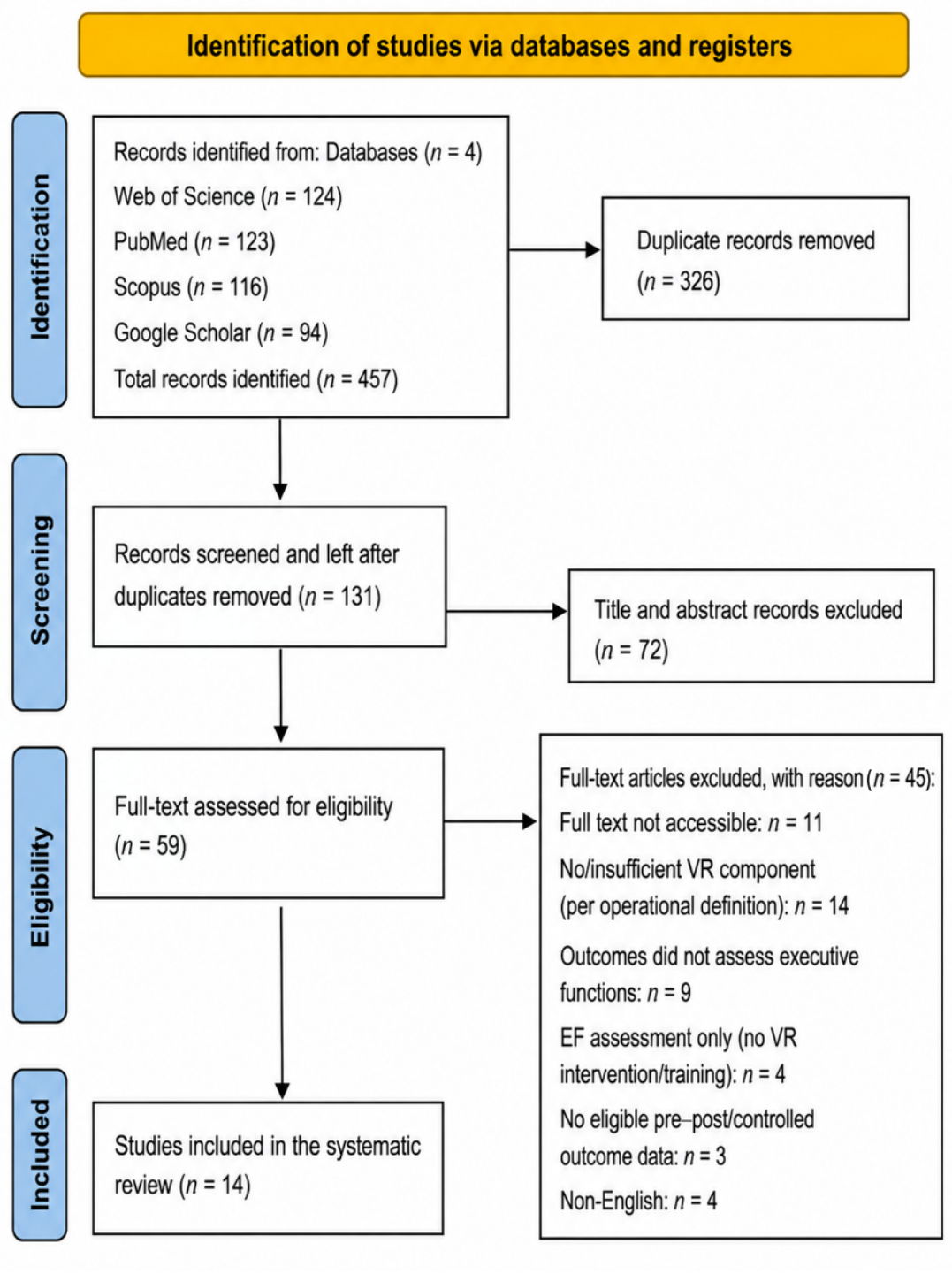


Figure 1. PRISMA 2020 flow diagram
Abbreviations: EF: Executive function; VR: Virtual reality.

For inclusion, studies had to report at least one EF outcome using a validated EF-specific task, subscale, or battery (e.g., inhibition, shifting/cognitive flexibility, working memory/updating, planning/problem solving). Studies reporting only global cognition measures without separable EF indices were considered to provide limited EF-specific inference. These were retained only if the authors explicitly reported EF-related subdomains or EF-relevant task outcomes (Figure 1).

2.6. Risk of bias assessment

Risk of bias was assessed independently by two reviewers (N.Dr and P.P) using design-appropriate tools. Randomized controlled trials were assessed using the Cochrane Risk of Bias 2 tool (version 22 August 2019, Cochrane, United Kingdom), whereas non-randomized intervention studies were evaluated using the ROBINS-I tool (version 2016, Cochrane, United Kingdom). The reviewers independently completed domain-level assessments and resolved disagreements through discussion and consensus, with consultation of a third reviewer (A.P) when necessary.

Randomized controlled trials, including pilot trials, were assessed using the Cochrane Risk of Bias 2 (RoB 2) tool across five domains: (i) bias arising from the randomization process, (ii) bias due to deviations from intended interventions, (iii) bias due to missing outcome data, (iv) bias in measurement of the outcome, and (v) bias in selection of the reported result. Each domain was judged as low risk, some concerns, or high risk, leading to an overall RoB 2 judgment for each study. Nonrandomized intervention studies, including single-group pre–post studies, were assessed using the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) tool across seven domains: (i) bias due to confounding, (ii) bias in selection of participants into the study, (iii) bias in classification of interventions, (iv) bias due to deviations from intended interventions, (v) bias due to missing data, (vi) bias in measurement of outcomes, and (vii) bias in selection of the reported result. ROBINS-I judgments were rated as low, moderate, serious, or critical risk of bias. The study-level risk-of-bias assessments are summarized in Table 2.

3. Theoretical background

3.1. Executive functions

Executive functions are interconnected higher-order control processes that support goal-directed behavior and adaptive cognition. Their expression varies across individuals and contexts and may be influenced by factors such as motivation, fatigue, and task difficulty.[27] Core EF components include working memory, inhibitory control, and cognitive flexibility, which enable individuals to maintain goals, suppress irrelevant responses, and adapt their behavior when task demands change.[28]

Working memory refers to the temporary maintenance and manipulation of information and is closely associated with attentional control.[29,30] Attention supports EF through the monitoring and selection of goal-relevant information and includes focused, sustained, selective, alternating, and divided components.[31,32]

Self-regulation integrates the planning, monitoring, and adjustment of behavior in response to internal goals and external demands[33], while cognitive flexibility supports shifts between perspectives, rules, and response strategies.[34] Planning and problem solving require the coordinated formulation of goals, selection of actions, and integration of attention, memory, and contextual information.[11,35–37] Inhibitory control supports the suppression of inappropriate or prepotent responses[38], whereas higher-order reasoning enables abstraction, relational integration, and the development of strategies beyond immediate task demands.[35,39]

Executive function performance is supported by distributed networks involving the prefrontal cortex and related brain systems and may be influenced by stress-related physiological processes.[12] EF is also commonly differentiated into relatively emotionally neutral "cold" processes and motivationally or emotionally salient "hot" processes.[27,33] Evidence that EF can improve through structured practice provides the conceptual basis for interventions, including VR-based programs that repeatedly engage goal maintenance, inhibition, and flexible adaptation through structured, feedback-rich tasks.[1,20,27,38]

3.2. Virtual reality

Virtual reality refers to interactive, computer-generated environments that can provide users with a subjective sense of presence within a simulated setting.[31] Advances in graphics processing, motion tracking, display technology, and portable computing have expanded the accessibility and application of VR across research, rehabilitation, and cognitive training.[40-43]

Virtual reality systems vary according to their display and interaction configuration. Fully immersive systems commonly use HMDs, whereas semi-immersive and non-immersive systems may use desktop or large-screen interfaces combined with controllers or motion tracking.[4,44,45] Although non-immersive systems provide lower levels of sensory immersion, they may offer advantages in usability, cost, accessibility, and tolerability. Accordingly, this review included fully immersive, semi-

immersive, and non-immersive applications in which VR served as a central intervention component and EF-related outcomes were assessed.

Virtual reality has been used in simulation-based education and experiential training, although its implementation may be influenced by usability, instructional design, and user familiarity.[46,47] Ecologically structured virtual environments have also been applied to EF rehabilitation[48], while controlled virtual social interactions have been examined in clinical interventions.[49] In neuropsychological research, virtual environments have supported attention assessment under realistic distraction conditions[50], the evaluation of EF through complex everyday tasks[51], HMD-based training and assessment[52], and the collection of detailed digital behavioral data.[53]

A central concept in VR is presence, defined as the subjective experience of being located within the virtual environment. Presence is affected by display characteristics, sensory feedback, and the correspondence between user actions and virtual outcomes.[54-56] Interaction fidelity concerns the extent to which users can act naturally within the environment, although greater fidelity does not necessarily improve performance across all tasks or populations.[57-59] Place illusion and plausibility further explain how coherent perceptual and action–outcome relationships may produce realistic responses in immersive settings.[60] Presence can be assessed using validated measures that examine spatial presence, engagement, ecological validity, and negative effects.[61,62]

For EF applications, VR combines realistic task settings with experimental control over difficulty, distraction, feedback, and progression.[24,25,54] It may also allow motivationally neutral and emotionally salient executive demands to be manipulated under controlled conditions.[63,64] VR-based EF applications have consequently been developed for populations with neurological, neurodevelopmental, and age-related executive difficulties[65,66] and for the systematic manipulation of switching, interference, multitasking, and time pressure.[67,68] Nevertheless, transfer beyond the trained virtual activities should be established through functional outcomes and follow-up assessment rather than inferred from environmental realism alone[10,66] (Figure 2).

3.3. Differential effects of virtual reality on executive functions

Virtual reality may influence EF through a combination of immersion and presence, immediate performance feedback, adaptive task difficulty, embodied interaction,

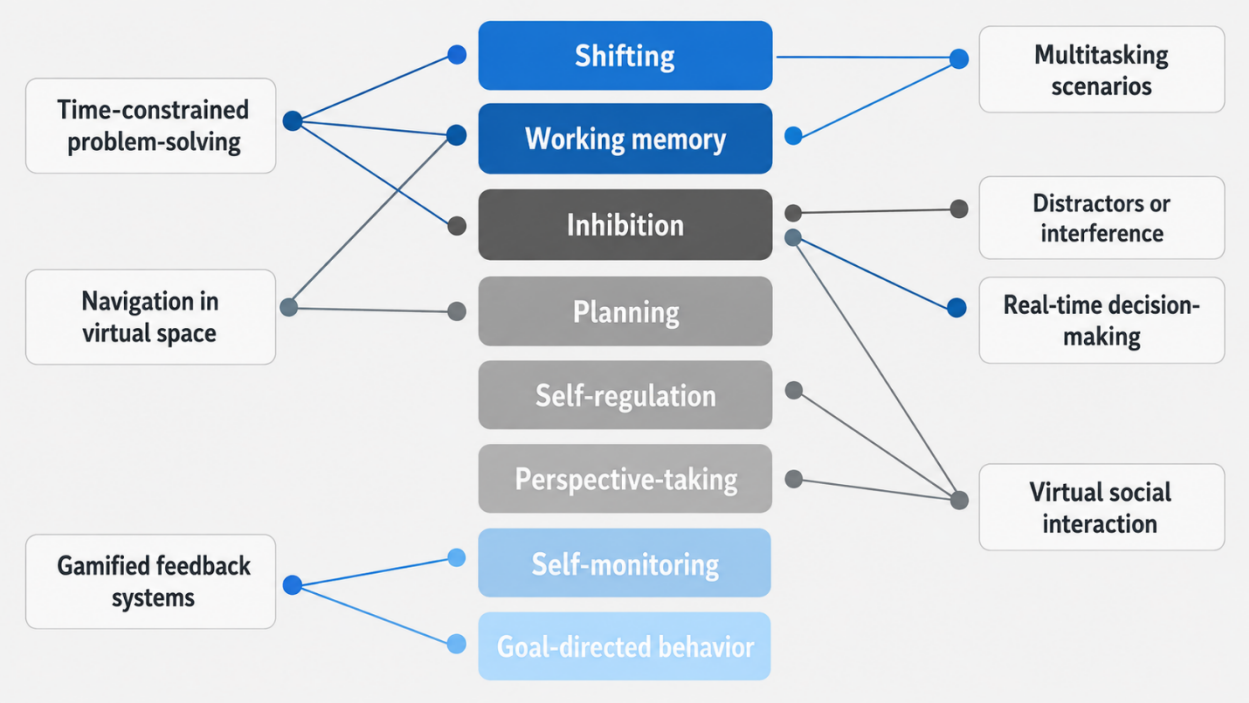


Figure 2. Mapping of immersive features to targeted executive function domains

and the simulation of complex everyday activities. However, these characteristics should be regarded as plausible mechanisms of action rather than evidence that VR is inherently superior to conventional cognitive training.

(i) Immersion and presence: Immersion refers primarily to the objective technological characteristics of a system, whereas presence describes the subjective experience of being located and acting within the virtual environment.[69,70] Greater immersion may increase attentional engagement and perceived realism, but it does not necessarily produce better cognitive outcomes. Experimental research has shown that highly immersive environments can increase presence while simultaneously increasing cognitive load or reducing learning performance, and that presence does not consistently mediate the relationship between immersion and memory.[71,72] Therefore, immersion should be matched to the cognitive demands of the task and users' characteristics rather than treated as an intervention benefit in itself.

(ii) Feedback and real-time adaptation: VR systems can provide immediate audiovisual feedback and adjust task complexity, pacing, distractor density, and response requirements based on users' performance. Adaptive EF training can generate robust improvement in the directly trained tasks, although transfer to untrained executive measures is often more limited.[73] Clinical studies using adaptive motion-interaction platforms and VR-based simulations of activities of daily living have also demonstrated the feasibility of progressively adjusting task demands, feedback, and cueing during executive and multidomain cognitive rehabilitation.[74,75] These findings suggest that adaptivity may help maintain an appropriate level of challenge, although its effectiveness depends on whether the adaptive rules specifically engage the executive process targeted by the intervention.

(iii) Embodiment and sensorimotor integration: Immersive VR can create a sense of ownership and agency over a virtual body when users experience the environment from a first-person perspective and receive congruent visuomotor or visuotactile feedback.[76-78] In EF training, embodied interaction may connect cognitive demands with purposeful action, requiring participants to maintain goals, select responses, monitor outcomes, and modify their behavior as environmental conditions change. Nevertheless, evidence that embodiment itself produces superior EF improvement remains limited, and its contribution should be distinguished from the effects of task practice, feedback, and increased engagement.

(iv) Ecological validity and transfer: VR permits executive processes to be assessed and trained within complex scenarios that approximate everyday activities while preserving experimental control. Virtual city tasks involving errands, planning, and multitasking have demonstrated preliminary ecological validity in both healthy participants and individuals with acquired brain injury.[79,80] Intervention studies using virtual shopping and activities-of-daily-living scenarios have also reported improvements in EF, instrumental activities of daily living, or related functional outcomes among individuals with MCI and cognitively vulnerable older adults.[81-83] However, similarity to real-life activities does not automatically establish transfer. Transfer should be demonstrated through improvements in untrained executive measures, functional performance outcomes, and follow-up assessments rather than inferred solely from the realism of the virtual environment.

Overall, VR should be understood as a flexible intervention platform whose effects depend on the alignment between the targeted executive process, task design, immersion level, feedback schedule, adaptive progression, participant characteristics, intervention dose, and outcome measurement. Technological sophistication alone does not establish therapeutic effectiveness; the central question is whether a specific VR configuration engages the intended executive process and produces improvements that generalize beyond the trained activity and remain evident over time.

3.4. Working memory in rehabilitation

Working memory supports the temporary maintenance and manipulation of information required for goal-directed activity. Baddeley's[84] multicomponent model describes working memory as a coordinated system in which temporary storage components operate alongside an executive-control component. This framework is relevant to rehabilitation because everyday activities frequently require individuals to maintain goals, resist distraction, and update ongoing plans.

3.5. Technology-enhanced cognitive training

Technology-enhanced cognitive training has been proposed as a response to common limitations of traditional cognitive rehabilitation approaches, which are often characterized by repetitive exercises, reduced engagement over time, and limited ecological validity. In a systematic review of computerized cognitive training in older adults, Kueider *et al.*[85] highlighted that technology-supported programs can provide structured, repeatable practice while enhancing

engagement and motivation through interactive task formats. Computer-based and game-based interventions, in particular, can deliver standardized training with adaptive difficulty and immediate performance feedback, which may enhance learning and support cognitive change through sustained practice.[85]

More recently, immersive technologies have extended this approach by providing environments that more closely approximate everyday cognitive demands. Clinical VR has been described as a promising modality because it allows users to train within interactive, realistic simulations while maintaining experimental control over task parameters, feedback, and progression.[86] Compared to traditional computerized tasks, VR can combine multimodal cues and goal-driven actions within richly contextualized scenarios, which may increase engagement and promote practice that closely mirrors real-life situations.[86,87] However, VR-based training still faces practical limitations such as tolerability, accessibility, and implementation challenges. These practical limitations highlight the need to select technology carefully, ensuring it aligns with user needs and targets the relevant cognitive domains.[86,87]

3.6. Virtual reality in rehabilitation

Virtual reality-based rehabilitation enables repeated practice of functional, goal-oriented activities in safe, controlled environments. Evidence from neurological rehabilitation indicates that VR interventions are feasible and may support rehabilitation outcomes through interactive and task-oriented practice.[88] Their potential clinical value lies in combining standardization and progressive adaptation with simulations of meaningful everyday activities. However, the transfer of trained strategies to daily functioning depends on intervention dose, task variability, outcome selection, and follow-up assessment.[89] More broadly, EF is relevant to real-world adaptation; among university students, it has been shown to predict academic, although not social, adjustment.[90]

3.7. Mechanisms linking virtual reality to executive functions

Several mechanisms have been suggested to explain how VR-based interventions might influence EF. First, VR tasks often combine multisensory stimulation with continuous perception–action coupling, requiring users to process visual, auditory, and motor information while maintaining goals and adapting to changing demands. These combined cognitive and sensorimotor demands may enhance engagement of executive control processes such as attention, inhibition, and flexible updating, especially when VR involves active navigation, rule adherence, and response selection under distraction.[86] Second, VR environments are often embedded in game-like, interactive scenarios that boost engagement and reduce boredom, which can improve adherence and increase effective practice time, a crucial factor since cognitive improvements generally require repeated, sustained training.[86] Third, VR may enhance ecological validity by simulating daily activities (e.g., shopping, cooking, navigation), offering realistic practice opportunities for executive control that resemble real-world situations. This design could support the transfer of strategies to real-world daily tasks, although such transfer varies and is inconsistently assessed across studies.[87] Fourth, many VR systems include adaptive difficulty or therapist-guided progression, allowing for personalized adjustment of cognitive load. By maintaining tasks that are challenging yet achievable, adaptive training can keep users in an optimal learning zone, promoting the development of executive skills across diverse ability levels and clinical conditions.[6,26]

Despite these plausible mechanisms, the empirical studies vary widely in target populations, intervention dose and content, outcome measures, and follow-up assessments. Some studies report improvements in EF-related outcomes such as inhibition, switching, and prospective memory after VR-based cognitive training, whereas others report only modest, task-specific, or short-term effects.[2,3,19,91] Additionally, it remains unclear whether VR provides unique benefits for clinical groups compared to healthy older adults, or which combinations of immersion level, task design, and training dose most reliably yield transferable EF improvements. This variability highlights the need for systematic analysis to better understand the scope, effectiveness, and limitations of VR methods for enhancing EF.[4]

4. Results

4.1. RQ1: What types of virtual reality tools were used?

The included studies examined VR-based EF interventions across neurological, neurodevelopmental, neuropsychiatric, and non-clinical populations. Clinical samples included participants with stroke, TBI, Parkinson's disease, MCI, MS, schizophrenia- or psychosis-spectrum disorders, and ADHD, whereas non-clinical samples included healthy adults and community-dwelling older adults. The 14 included studies used heterogeneous VR technologies ranging from non-immersive and semi-immersive screen-based or telerehabilitation platforms to fully immersive HMD-based systems. Non-immersive and semi-immersive applications commonly used desktop displays, touchscreens, motion-tracking cameras, or dedicated rehabilitation interfaces and were primarily

Table 2. Risk of bias summary for included studies

Study	Tool	Randomization process/confounding	Deviations from intended interventions	Missing outcome data	Outcome measurement	Selective reporting	Overall risk of bias
Maier *et al.*[26]	RoB 2	Some concerns	Some concerns	Low	Some concerns	Some concerns	Some concerns
Maggio *et al.* [92]	RoB 2	Some concerns	Some concerns	Low	Some concerns	Some concerns	Some concerns
De Luca *et al.*[3]	RoB 2	Some concerns	Some concerns	Some concerns	Some concerns	Some concerns	Some concerns
Maggio *et al.*[93]	RoB 2	Some concerns	Some concerns	Low	Some concerns	Some concerns	Some concerns
Fiorenzato *et al.*[2]	RoB 2	Low	Some concerns	Low	Some concerns	Some concerns	Some concerns
Park *et al.*[91]	RoB 2	Some concerns	Some concerns	Some concerns	Some concerns	Some concerns	Some concerns
Park *et al.*[94]	RoB 2	Some concerns	Some concerns	Some concerns	Some concerns	Some concerns	Some concerns
Thapa *et al.*[19]	RoB 2	Some concerns	Some concerns	Low	Some concerns	Some concerns	Some concerns
Zaragoza-Mezquita *et al.*[95]	ROBINS-I	Serious	Moderate	Moderate	Moderate	Moderate	Serious
Komemi *et al.*[96]	ROBINS-I	Serious	Moderate	Moderate	Moderate	Moderate	Serious
Bisso *et al.*[97]	RoB 2	Some concerns	Some concerns	Low	Some concerns	Some concerns	Some concerns
Schena *et al.*[98]	ROBINS-I	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Huang[99]	ROBINS-I	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Makmee *et al.*[67]	RoB 2	Some concerns	Some concerns	Low	Some concerns	Some concerns	Some concerns

Notes: RoB 2 = Cochrane Risk of Bias tool for randomized trials; ROBINS-I = Risk of Bias in Non-randomized Studies of Interventions. "Some concerns" ratings in virtual reality studies commonly reflect limited blinding feasibility, small pilot samples, and incomplete reporting of allocation concealment and preregistered analysis plans.

implemented in stroke, TBI, Parkinson's disease, and schizophrenia-spectrum rehabilitation.[3,26,92,93,96,97] Fully immersive interventions used HMDs and handheld controllers to deliver interactive environments for participants with Parkinson's disease, MCI, MS, ADHD, and general or older-adult populations.[2,19,67,94,95,98,99]. One cognitive–motor rehabilitation system additionally combined virtual daily-life activities with purpose-built physical controls.[91]

Across immersion levels, interventions commonly incorporated ecologically framed scenarios, including supermarkets, homes, transport settings, and other everyday activities.[2,3,19,26,67,91–99] Several systems provided automated or therapist-guided adaptation of task difficulty, immediate audiovisual feedback, performance monitoring, and remote supervision.[2,3,26,92,93,96] These findings indicate that the defining features of the reviewed interventions were not immersion alone but the combination of structured executive demands, interactive feedback, progressive challenge, and contextually meaningful tasks. Across the included studies, VR tools ranged from non-immersive, screen-based systems to semi-immersive or telerehabilitation platforms to fully immersive HMDs. This indicates significant differences in hardware, interaction techniques, and delivery settings.

- Non-immersive (screen-based) VR systems: Several studies used VR delivered on a computer monitor or touchscreen (without an HMD), often paired with handheld controllers or motion tracking (e.g., Microsoft Kinect) to enable interaction with virtual environments such as supermarkets, daily life simulations, or task-based training modules.[3,26,93,96,97]
- Semi-immersive and VR tele-rehabilitation platforms: Some interventions used structured clinical-grade platforms (notably VRRS/VRRS Evo) that provide screen-based cognitive exercises with therapist-led progression and, in some cases, home-based tele-rehabilitation supported by remote monitoring and real-time adjustment through clinician interfaces.[3,92,93]
- Fully immersive VR (HMD-based): Many studies implemented immersive VR via HMDs (e.g., Oculus/Meta devices, HTC Vive, Oculus Rift/Go) combined with hand controllers (and sometimes room-scale tracking) to deliver first-person cognitive training in realistic, interactive environments.[2,19,67,92,94,95,98,99]
- Game-based and ecologically valid scenario design: Regardless of immersion level, VR content commonly uses serious games, exergames, or real-world simulations (e.g., home tasks, shopping/supermarket scenarios, culturally themed activities) to approximate everyday executive demands and increase engagement.[2,19,26,67,91-99]
- Adaptive difficulty and feedback features: Many systems incorporated real-time feedback (audiovisual cues, success/error signals, session summaries) and/or adaptive difficulty to individualize challenge level based on performance, supporting personalized training across heterogeneous users and clinical populations.[2,3,26,92,93,96]

4.2. RQ2: What effects did virtual reality-based interventions have on executive-function outcomes?

Maier *et al.*[26] observed that 75% of chronic stroke patients had deficits across multiple cognitive domains initially. Following six weeks of adaptive conjunctive VR cognitive training, participants improved in attention, spatial awareness, and overall cognition. No significant changes in memory or EF were detected. Depression increased during therapy but normalized at follow-up, with the experimental group eventually showing less depression than controls.

Maggio *et al.*[92] reported that executive cognitive functions were not assessed with a dedicated EF battery (e.g., separate inhibition, shifting, or planning tests); instead, overall cognition, including an executive component, was evaluated using the Montreal Cognitive Assessment (MoCA). The VRRS group showed a significant pre–post improvement on the MoCA, suggesting an overall gain in cognitive functioning, including executive abilities assessed by the MoCA. The control group also improved significantly on the MoCA, and importantly, the between-group comparison showed no significant difference, indicating that the VR intervention did not outperform traditional training on the global cognitive outcome measure.

De Luca *et al.*[3] found that executive cognitive functioning improved significantly within the VR cognitive training group (VR CT) from baseline (T0) to post-treatment (T1) across multiple executive/attention related measures, including the Frontal Assessment Battery (FAB) and Trail Making Test (TMT) indices, alongside improvement in global cognition (MoCA). However, when comparing the magnitude of improvement between VR CT and conventional cognitive training, the only executive/attention outcome that showed a statistically significant between-group advantage was TMT B–A (with a significant post-treatment difference and a large effect size reported). At the same time, FAB and the other TMT measures did not differ significantly between groups despite improving within the VR CT group.

In Maggio *et al.*'s[93] research, executive–cognitive functioning was not reported as a separate outcome. The

study used the MoCA as its primary cognitive measure, which provides a global cognition score that includes some executive components. Still, it does not isolate EF as a standalone endpoint in the results. Accordingly, the study's cognitive findings are presented as overall MoCA improvement, with the experimental (VR + tele rehab) group showing a significantly greater MoCA gain than the control group, as indicated by Δ scores (T1–T0). While the intervention included exercises targeting EF (e.g., planning/problem-solving tasks), the results do not permit conclusions about which specific cognitive domains (including EF) improved because no domain-specific executive tests or subscores were analyzed or reported.

Fiorenzato *et al.*[2] reported that the immersive VR EF training produced selective improvements in executive cognitive functioning, rather than broad gains across all EF measures. In Parkinson's disease patients with MCI (PD CT), Fiorenzato *et al.*[2] reported a significant group × time effect on an inhibition measure, specifically the Stroop test (total time), indicating better inhibition performance in the EF training group compared with the active placebo group; this interaction was significant at post-intervention (T1) and showed a trend at 2-month follow-up (T2), while other attention/executive tests did not show significant group × time interaction effects. In healthy older adults (HC CT), the clearest executive outcome was an improvement in planning, evidenced by a significant group × time interaction in the Zoo Map test, with improvements maintained at both post-intervention and follow-up, whereas the HC active placebo group did not show comparable change.

In a study of older adults with MCI, Park *et al.*[91] showed that executive cognitive functioning, operationalized primarily by performance on the TMT-B, improved following VR-based cognitive–motor rehabilitation. Specifically, the VRCMR (MOTOCOG®) group demonstrated a significant pre–post reduction in TMT-B completion time, whereas the conventional cognitive rehabilitation (CCR) group did not show a statistically significant pre–post change. Importantly, the between-group post-intervention comparison indicated that the VRCMR group improved significantly more than CCR on TMT-B, alongside improvements in global cognition (MoCA) and attention/working memory indices (e.g., Forward Digit Span [FDS]), suggesting that the VR cognitive–motor approach produced stronger gains in executive/attentional processing speed and cognitive flexibility than conventional tabletop training in older adults with MCI.

Park *et al.*[94] found that the culture-based VR program did not produce significant improvements in executive cognitive functioning following the 12-week intervention. EF was assessed using frontal lobe measures, including the Korean Color–Word Stroop test and word fluency tests. The results showed no significant group (group × time) effects and no significant within-group changes in these executive outcomes following training. In other words, despite good feasibility/adherence and tolerability, the VR group did not show measurable gains in inhibition/processing (Stroop) or in verbal executive control (fluency) relative to baseline or controls.

Thapa *et al.*[19] reported that executive cognitive functioning, primarily indexed by the TMT-B, improved following the VR game intervention. Specifically, the intervention group showed a significant reduction in TMT-B completion time from baseline to the post-intervention assessment. This improvement was significantly greater than that of the control group (group × time interaction), indicating a beneficial effect of the VR training on executive processes related to working memory and cognitive flexibility. In contrast, changes in other cognitive measures (e.g., Mini-Mental State Examination and TMT-A) were smaller and not consistently significant relative to controls, suggesting the most robust executive gain was observed on TMT-B.

Zaragoza-Mezquita *et al.*[95] reported that executive–cognitive functioning (particularly working memory, information processing speed, and cognitive flexibility/attentional control) improved following immersive VR training. Specifically, when participants (people with MS and healthy controls) were compared from pre- to post-training, there were significant performance gains on non-trained neuropsychological measures indexing executive–cognitive abilities, especially the Letters–Numbers Sequencing Test (LNST) and the MS relevant processing speed/working memory measures Paced Auditory Serial Addition Test (PASAT) and Symbol Digit Modalities Test (SDMT); importantly, these improvements were observed in both groups (i.e., a main effect of evaluation time without a clear group × time interaction), suggesting transferable benefits of repeated VR practice rather than changes limited to only one group. Additionally, the authors reported that larger improvements on the more demanding VR task levels correlated with larger gains on LNST, PASAT, and SDMT, further supporting transfer to executive–cognitive processes such as working memory and processing speed.

Komemi *et al.*[96] reported significant improvement in executive–cognitive functioning after ecological VR-based cognitive remediation; however, interpretation is limited by the single-group (no control) pilot design. Post-intervention, participants improved on trained executive

components within the Functional Brain Trainer, including multitasking and spatial working memory, and they also demonstrated improvements on standard neuropsychological "near transfer" measures that index EF, most notably cognitive flexibility on TMT-B and verbal fluency on the Category Fluency Test, alongside gains in processing speed (TMT-A) and visuomotor organization.

In a study by Bisso *et al.*[97], schizophrenia inpatients who received six weeks of non-immersive VR cognitive training (two ecological scenarios: "Supermarket" and "Beach") showed the clearest executive cognitive benefit on frontal/EF, indexed by the FAB. Bisso *et al.*[97] reported a significant arm effect and a significant arm × timepoint interaction in the mixed-effects model, supported by a significant between-group difference at post-intervention (T1), indicating greater FAB improvement in the VR group than in the treatment-as-usual group. In contrast, broader executive/attention measures showed weaker effects: TMT-B demonstrated a significant timepoint effect (improvement over time in both groups), while effects on TMT B–A and Tower of London (TOL) did not remain statistically significant after Benjamini–Hochberg correction, although trends were noted. In addition to these test outcomes, scenario-based training metrics improved across sessions, with reductions in execution time, errors/omissions, and need for aids, suggesting learning and improved task performance within the trained VR activities.

Schena *et al.*[98] reported that the VR serious game intervention produced statistically significant pre–post improvements in executive–cognitive functioning. Specifically, on the TOL outcomes, participants showed significant gains in organization/planning and problem solving, alongside a significant improvement in the overall EF index from baseline (T0) to post-treatment (T1). In addition to these executive changes, the authors also reported improvements in attention-related and self-regulatory variables (e.g., reductions in impulsive behavior and improvements in sustained/selective attention), supporting a broader enhancement of executive control processes following the VR intervention.

Huang[99] found that immersive VR exergaming produced greater improvements in selected EF than non-immersive exergaming; however, these benefits emerged only after the four-week training period rather than immediately. After a single training session, there were no significant between-condition differences on any of the EF measures. However, after participants completed the full four-week program, the immersive condition showed significantly greater gains in inhibitory control (Stroop test) and task switching/cognitive flexibility (TMT score), with significant effects reported for both outcomes (supported by intention-to-treat analyses using conservative missing-data approaches). In contrast, there was no significant improvement in working memory as measured by Backward Digit Span (BDS), indicating that the immersive VR advantage was specific to inhibition and switching rather than extending to all executive subdomains.

Makmee *et al.*[67] demonstrated that the VR-based cognitive intervention produced overall positive effects on EF, particularly on the EF components of inhibition, updating, and shifting. Statistically, the training group showed a significant group × time interaction for Go/No-Go reaction time (the processing speed component of inhibition), indicating that post-test performance differed from that of the control group with a moderate effect size. In contrast, response accuracy did not show a significant interaction. The intervention also improved updating, as shown by significant group × time effects in the FDS for both memory span (large effect) and reaction time (moderate effect), whereas BDS outcomes did not show significant group × time effects, suggesting no clear benefit for the more demanding "active updating" component. Finally, for shifting/cognitive flexibility, the training group demonstrated significantly better post-test performance on the Berg Card Sorting Test (BCST) in response accuracy than controls (moderate effect).

Across the 14 studies, VR-based interventions produced heterogeneous but generally encouraging effects on executive–cognitive functions, with the most consistent benefits appearing in inhibition, cognitive flexibility/shifting, and planning, while effects on working memory/updating were more variable. In stroke populations, executive outcomes were mixed: Maier *et al.*[26] reported significant gains in attention and spatial awareness, but no significant change in EF as a distinct domain, and Maggio *et al.*[92] showed global cognitive improvement on MoCA in both VR and control conditions without a clear VR superiority, limiting conclusions about EF-specific change. In Parkinson's disease, Fiorenzato *et al.*[2] found selective executive improvements rather than broad EF gains, most notably an inhibition effect on Stroop total time in Parkinson's disease with mild cognitive impairment (PD-MCI) and improved planning (Zoo Map) in healthy older adults, whereas Maggio *et al.*[93] primarily reported global MoCA improvement (with greater gains in the VR/tele rehab group) without isolating executive domains through a dedicated EF battery.

Evidence was stronger in several non-stroke groups when EF was measured with domain-relevant tests. In TBI, VR training produced within-group improvements across executive/attention measures, but the clearest between-

group advantage was observed for TMT B–A, suggesting a specific benefit for executive control/switching beyond conventional training [3]. Among older adults with MCI, VR cognitive–motor rehabilitation led to significantly greater improvement on TMT-B than conventional cognitive training, indicating stronger gains in cognitive flexibility/processing efficiency.[91] In contrast, a culture-based immersive VR program did not significantly improve Stroop or fluency outcomes.[94] In other populations, immersive VR game training improved TMT-B,[19] immersive VR in MS was associated with pre–post gains in executive-related measures (e.g., LNST, PASAT, SDMT), though improvements were not always group-specific,[95] and ecological VR remediation in schizophrenia showed pre–post improvements in executive measures (e.g., TMT-B, fluency). Still, interpretation is constrained by the single-group pilot design.[96] Additional studies re-ported EF benefits in specific subdomains: Bisso *et al.*[97] found a robust VR advantage on FAB (with weaker/nonspecific effects on other executive tests), Schena *et al.*[98] showed improvements in planning/problem solving (TOL), Huang *et al.*[99] demonstrated that immersive VR exergaming improved inhibition and switching only after repeated training (not after one session), and Makmee *et al.*[67] reported improvements in inhibition speed (Go/No-Go RT), aspects of updating (FDS), and shifting (BCST accuracy). Overall, the body of evidence suggests VR can enhance selected executive processes, but effects vary by population, intervention design, and the specificity of EF measurement.

4.3. RQ3: To what extent were intervention effects maintained over time?

Intervention duration varied substantially across studies, ranging from short protocols of approximately 2 weeks to programs lasting approximately 6 months, although most interventions lasted 4–12 weeks. Most studies assessed outcomes only immediately after treatment, providing evidence of short-term change but no information regarding maintenance.[3,19,67,91–99]

Only a small number of studies included post-intervention follow-up. Maier *et al.*[26] reported delayed or maintained patterns following VR cognitive training in chronic stroke, while Fiorenzato *et al.*[2] observed maintenance of selected benefits in participants with Parkinson's disease and healthy older adults. Because follow-up timing and outcome selection differed across studies, the available evidence does not permit firm conclusions regarding the duration of VR-related EF improvements. Long-term maintenance therefore remains insufficiently established.

More specifically, across the examined papers, intervention duration varied substantially (from 2 weeks to ~6 months), but most studies assessed outcomes primarily as short-term pre–post effects, measured immediately at the end of training. The majority of protocols lasted 4–12 weeks and typically involved 2–3 sessions per week or structured multi-session schedules, with total "dose" commonly ranging between 8 and 24 sessions.[2,3,19,67,91-94,96,97,99] Only a small subset included any follow-up assessment beyond immediate post-treatment, which limits conclusions about the maintenance, decay, or delayed emergence of executive–cognitive benefits in most clinical populations.[3,19,67,91,94,96-99]

Among the studies that did include follow-up, the clearest evidence for sustained duration effects came from Maier *et al.*[26] (chronic stroke) and Fiorenzato *et al.*[2] (Parkinson's disease/healthy aging). In Maier *et al.*[26], improvements were most evident at follow-up: attention gains were significant at the later time point, spatial awareness improved both immediately and at follow-up, and generalized cognition improved at both post-treatment and follow-up, suggesting that some benefits were maintained and potentially strengthened over time. In Fiorenzato *et al.*[2], outcomes were assessed at baseline, post-intervention, and at a 2-month follow-up, with key gains in executive-related outcomes (e.g., inhibition and planning) reported as maintained at follow-up, indicating persistence beyond the training window. In contrast, most other studies spanning stroke rehabilitation without follow-up[92], TBI[3], MCI/older adults[91], culture-based VR in older adults[94], immersive VR gaming[19], MS[95], schizophrenia spectrum[96], non-immersive VR training[97], ADHD serious gaming (~6-month program but still evaluated pre–post only)[98], immersive vs. non-immersive exergaming[99], and immersive cognitive training in older adults[67], reported effects only immediately after intervention, making long-term retention uncertain.[3,19,91,92,94-99] Finally, in Parkinson's disease, telerehabilitation using VRRS [93] evaluated outcomes only before and after the 8-week program, providing evidence of immediate benefit but not of longer-term durability. Overall, the duration evidence indicates that VR interventions can produce measurable short-term changes across diverse populations. However, the field remains limited by the scarcity of follow-up testing, with sustained effects currently supported most clearly in the few studies that incorporated follow-up designs.[2,26] Table 3 summarizes the included studies.

5. Discussion

This systematic review synthesized evidence from 14 empirical studies (published between January 1, 2015, and December 31, 2025) examining VR interventions

Table 3. Summary of the included studies for analysis

Study	Study design	Population	Intervention	Duration	EF domains targeted	Key findings	Duration effects
Maier *et al.*[26]	Randomized controlled pilot trial	Chronic stroke with cognitive impairment (n≈30)	Desktop-based embodied VR (RGS) with motion capture + eye tracking	6 weeks; ~30 min/day, 5 days/week	Attention, spatial awareness, EF	Improved attention/spatial awareness; EF not clearly improved as a distinct domain	3-month follow-up
Maggio *et al.*[92]	Randomized controlled trial	Chronic stroke adults (n = 54; 27 per group)	VRRS cognitive rehabilitation vs. traditional cognitive rehabilitation	24 sessions, 3 per week, 8 weeks, ~45 min/session	EF within MoCA + task-specific VRRS EF activities	VR group improved motivation + MoCA + reduced anxiety/depression; between-group differences not significant overall	No long-term follow-up
De Luca *et al.*[3]	Pilot study (VR vs. conventional cognitive training)	Chronic TBI (n = 20)	VRRS–Evo non-immersive VR cognitive rehabilitation	24 sessions, 60 min, 3/week, 8 weeks	Visuo-executive abilities: categorization, planning, reasoning, problem solving; plus coping strategies	VR group improved MoCA, FAB, TMT A/B/BA, and mood; better gains than controls on some outcomes	No long-term follow-up
Maggio *et al.*[93]	Pilot randomized controlled trial	Parkinson's disease patients (+ caregivers outcomes) (n = 20)	VRRS telerehabilitation (screen-based; remote supervision via "Cockpit")	8 weeks; 24 sessions	EF often part of cognitive outcome battery	Greater MoCA gain in VR telerehab group; EF domains not isolated	No long-term follow-up
Fiorenzato *et al.*[2]	Randomized controlled trial (active placebo comparison)	PD-MCI + healthy older adults (n = 60)	Immersive iVR "virtual supermarket" via Oculus Go	4-week training	Inhibition, planning; prospective memory	PD-MCI improved prospective memory + inhibition; healthy older adults improved planning	2-month follow-up
Park *et al.*[91]	Randomized controlled study	Community-dwelling older adults with MCI (n = 40)	MOTOCOG® VR-based CMR (hardware + daily life tasks)	30 min/day, 5 days/week, 6 weeks	Attention/executive via TMT A/B; working memory via digit span	VR CMR improved motivation and cognition (MoCA, TMT, digit span) vs. control	No long-term follow-up
Park *et al.*[94]	Randomized controlled pilot study	MCI (n = 21)	Immersive VR via HTC Vive; culture-based VR games	30 min/day, 2 days/week for 3 months	EF within global cognition/attention batteries	Feasibility/tolerability supported; cognitive benefits mixed/limited depending on outcomes	No long-term follow-up
Thapa *et al.*[19]	Randomized controlled trial	Older adults with MCI (n = 68)	Fully immersive VR games via Oculus Quest	3×/week, 8 weeks; 24 sessions, 100 min/session	EF improved	Improved EF and resting state brain function; also gait/mobility improvements reported	No long-term follow-up
Zaragoza-Mezquita *et al.*[95]	VR cognitive training study (pre/post; includes controls)	Multiple sclerosis (n = 33) + healthy controls (n = 26)	Immersive VR platform (Ikinsu; HMD-based)	10 sessions; ~30 min each	Transfer to non-trained tests: memory, processing speed	Training improved VR task performance over days and improved non-trained neuropsychological tests (memory, processing speed) + motor outcomes	No long-term follow-up
Komemi *et al.*[96]	Pilot study	Inpatients with schizophrenia (initial recruited n = 31; 23 completers)	Functional Brain Trainer, Kinect-based motion-tracking	4 weeks; 8 sessions	EF-relevant cognitive remediation, verbal fluency	Pre–post improvements in flexibility/fluency	No long-term follow-up

(*Cont'd...*)

Table 3. (*Continued*)

Study	Study design	Population	Intervention	Duration	EF domains targeted	Key findings	Duration effects
Bisso *et al.*[97]	Randomized clinical trial	Inpatients with schizophrenia (n = 16)	Non-immersive VR scenarios (VR vs. TAU)	6 weekly sessions	Targets working memory, attention, EF; FAB & TMT used	Significant improvement on FAB; "trend level" gains for EF/attention; broader cognitive/symptom effects limited and attenuated after multiple comparison correction	No long-term follow-up
Schena *et al.*[98]	Experimental intervention study	Children with ADHD aged 5–12 (n = 30)	Meta Quest 2 (IAmHero); therapist monitoring via mirroring/streaming	Trial ~6 months; 24 weekly 30-min sessions	ADHD symptoms + EF outcomes	Improved planning/organization and EF index	No long-term follow-up
Huang[99]	Intervention study comparing immersive and non-immersive exergaming	Adults aged ≥ 50 years from a non-clinical population (n = 33)	Immersive Fruit Ninja VR (Oculus Rift) vs. non-immersive Fruit Ninja Kinect	2 sessions/week for 4 weeks	Working memory, cognitive flexibility	Significantly greater improvements in inhibitory control and cognitive flexibility/task switching than non-immersive exergaming. No significant improvement was found in working memory measured using Backward Digit Span. No significant between-condition differences were observed after a single session	No long-term follow-up
Makmee *et al.*[67]	Randomized controlled trial	Community-dwelling older adults aged 60–69 years (n = 60)	Immersive Oculus Quest + Unity3D everyday life tasks	8 sessions, 60 min, 2/week, 1 month	Working memory, attention, flexibility	Significant improvements in inhibition/updating/shifting vs. passive control	No long-term follow-up

Abbreviations: ADHD: Attention-deficit/hyperactivity disorder; CMR: Cognitive–motor rehabilitation; EF: Executive function; FAB: Frontal Assessment Battery; HMD: Head-mounted display; iVR: Immersive virtual reality; MCI: Mild cognitive impairment; MoCA: Montreal Cognitive Assessment; PD: Parkinson's disease; PD-MCI: Parkinson's disease with mild cognitive impairment; RGS: Rehabilitation Gaming System; TAU: Treatment as usual; TBI: Traumatic brain injury; TMT: Trail Making Test; VR: Virtual reality; VRRS: Virtual Reality Rehabilitation System.

doi: 10.36922/AN026290039

targeting EF across neurological, neurodevelopmental, neuropsychiatric, and non-clinical populations. The included studies covered conditions such as stroke, TBI, Parkinson's disease, MCI, MS, schizophrenia or psychosis-spectrum disorders, and ADHD, as well as healthy and community-dwelling older adults without a specified clinical diagnosis. Across these diverse contexts, three overarching conclusions emerged in relation to the review questions: (i) VR tools varied markedly in immersion level, interaction modality, and delivery context, with a clear trend toward ecologically framed, game-like training environments and increasing use of home-based delivery; (ii) VR interventions produced heterogeneous EF outcomes, with the most consistent improvements observed in inhibition, cognitive flexibility/shifting, and planning, while working memory/updating effects were mixed and strongly dependent on measurement specificity; and (iii) despite intervention durations commonly ranging from 4 to 12 weeks, most studies assessed outcomes only immediately post-intervention, leaving durability of EF gains largely uncertain, with sustained effects supported most clearly in the small subset of studies incorporating follow-up assessments.

5.1. Virtual reality technologies and design features that support executive function training

Regarding RQ1, VR tools vary from non-immersive, screen-based systems to semi-immersive telerehabilitation platforms and fully immersive HMD systems. This variety shows that EF-oriented VR does not require full immersion; instead, systems can be arranged along a spectrum balancing ecological validity, accessibility, cost, clinical practicality, and patient comfort. Non-immersive and semi-immersive systems, often used via monitors and touchscreens, and sometimes with motion tracking, are common in clinical rehabilitation, likely due to practical constraints in hospitals and outpatient settings and the need for therapist supervision. Simultaneously, several studies used fully immersive VR with HMDs and handheld controllers to create first-person interactions in realistic environments, such as supermarkets or home-like scenarios. Such immersive, first-person interactions may increase presence, engagement, and training that mimics everyday executive tasks.

Across different immersion levels, two features stood out. First, many interventions used realistic scenarios, such as shopping, household chores, and culturally relevant daily activities, often in serious game or exergame formats, which can enhance motivation, adherence, and the training of real-world EFs, such as goal management, planning, and handling distractions. Second, many systems featured adaptive difficulty and performance feedback, allowing personalized challenge adjustment and supporting learning across diverse users and impairment levels. These features align with current views of EF as context-dependent and sensitive to task complexity and cognitive load; training that dynamically adjusts demands may be especially beneficial for clinical populations, where tasks that are too easy or too difficult can limit gains.

5.2. Effects of virtual reality on executive functions: Patterns and measurement considerations

For RQ2, the overall results were promising but not consistent. Improvements were most frequently observed in EF components linked to executive control under interference, cognitive flexibility/shifting, and planning/problem solving. These areas are likely engaged by VR tasks that involve quick decision-making, maintaining goals amid competing cues, flexible rule updates, and multistep actions, all of which can be incorporated into interactive simulated environments. Conversely, evidence for changes in working memory/updating was more inconsistent, possibly due to genuine domain differences or methodological factors, such as the sensitivity and specificity of the working memory measures (e.g., forward vs. backward span) and whether the tasks explicitly targeted updating or broader attentional/EF.

A key interpretive challenge was the varied approaches to measuring EF. Many studies relied on broad cognitive screening tools such as the MoCA, which include executive components but do not precisely isolate EF domains. When MoCA was the main outcome, improvements might reflect overall cognitive gains, but they do not strongly support specific EF improvements. Conversely, studies using targeted EF tests, such as the TMT, Stroop interference, planning tasks such as Zoo Map or TOL, and frontal/executive composites such as the FAB, offered clearer evidence of which EF areas improved and whether these gains were greater than those of active controls. This measurement variability likely explains the mixed findings across clinical populations: in some cases, VR effects may remain undetected if the outcomes are not sensitive enough to detect EF changes or if they focus more on general cognition.

In addition to measurement issues, variations in participant populations and intervention content influenced results. Executive dysfunction profiles vary greatly among stroke, TBI, PD-MCI, MS, schizophrenia spectrum disorders, and ADHD, with VR applications tailored to different cognitive targets, motor demands, therapist involvement, and intensities. Interventions emphasizing frequent practice, adaptive difficulty, and ecologically valid executive challenges tended to produce

stronger EF related improvements. In contrast, programs that showed good feasibility but limited EF benefits might have lacked sufficient training intensity, mismatched task demands and EF targets, or measured outcomes less likely to change given the intervention's focus.

5.3. Duration and persistence of effects

For RQ3, most studies measured "duration" as the length of the intervention and evaluated effects only before and after training. This approach limits understanding of whether EF improvements continue after training ends. Only a few studies included follow-up assessments beyond immediate post-treatment, providing the clearest evidence that some cognitive and executive gains can be maintained for weeks or months. Notably, these few follow-up studies indicated that certain benefits might persist or even become more noticeable over time, suggesting that training effects may gradually consolidate and generalize as individuals apply learned strategies to everyday life. However, since follow-ups are rare and vary in timing (e.g., around 2 months vs. 3 months), current evidence does not allow for precise conclusions about the duration of VR-related EF improvements, which populations retain benefits the longest, or what level of intervention dose is needed for lasting change.

The lack of follow-up is especially important for clinical translation. Rehabilitation stakeholders need evidence not only of immediate post-treatment improvements but also of long-term functional relevance. Without extended follow-up, preferably including functional and real-world outcomes, it is challenging to assess whether VR interventions lead to lasting EF improvements or merely short-term gains on cognitive tests.

5.4. Potential mechanisms underlying virtual reality-supported changes in executive function

Although mechanisms were not uniformly tested across studies, several plausible pathways may explain why VR can support EF enhancement. First, VR enables repeated practice of goal-directed behavior in complex, dynamic environments that more closely approximate real-world executive challenges than many traditional computerized tasks. This ecological complexity may engage distributed executive control networks and promote strategy development that transfers beyond the trained task. Second, VR often increases motivation, engagement, and adherence, which are critical for cognitive rehabilitation effects that depend on repeated practice. Third, multimodal feedback and embodied interaction may support attentional control and learning by linking cognitive demands to perceptual and action contingencies. Finally, adaptive difficulty algorithms may maintain training within an optimal challenge range, which could be particularly important for individuals with EF impairments who are sensitive to cognitive overload or disengagement.

At the same time, these assumed benefits do not ensure better results. If VR tasks are poorly matched to the targeted EF, impose excessive motor demand, or are insufficiently intense, VR may not surpass active control methods. Therefore, the observed variability likely results not only from differences across populations but also from inconsistencies in intervention design, focus, and implementation fidelity.

5.5. Clinical and practical implications

From a practical standpoint, the findings suggest cautious optimism about VR as a tool for enhancing specific EFs across various populations, especially when used for ecologically valid, adaptable training under proper therapist supervision or structured remote oversight. Multiple studies show that VR can be effectively integrated into clinical and home environments, including telerehabilitation setups that enable real-time therapist adjustments. The feasibility of delivering adaptable, therapist-supervised VR training in home settings is particularly important because impairments in EF often hinder independent living and participation in rehabilitation; scalable home-based VR could broaden access to cognitive therapy while preserving personalization and engagement.

However, current evidence does not support the broad claim that VR consistently improves EF as a single construct across different conditions. Instead, benefits tend to be domain-specific and depend on measurement sensitivity, intervention content, and user characteristics. Clinicians and researchers should focus on ensuring alignment among the targeted EF domain(s), the VR task demands, and the outcome measures used, and should interpret improvements in global cognition as supportive but not conclusive evidence of specific EF change.

5.6. Limitations of the current evidence base and of this review

Several limitations affect interpretation. First, the studies varied considerably in VR systems (such as immersion, interfaces, platforms), intervention dose and intensity, participant populations, impairment severity, and outcome measures. This diversity hampers comparability and makes it difficult to determine which VR setups are most effective. Second, many studies used pre–post designs or lacked robust active control groups, and some had small sample sizes, which increases bias risks and reduces statistical power. Third, EF outcomes were not always measured with comprehensive, domain-specific batteries, and the

widespread use of global cognitive screening tools reduced the specificity of EF measurement. Fourth, follow-up assessments were rare, limiting conclusions about long-term effects. Finally, many studies reported mainly cognitive test results, with limited evidence showing that VR-driven improvements in EF translate to functional gains in daily life.

This review is also limited by the eligibility criteria for the included literature (English-language, peer-reviewed publications from January 1, 2015, to December 31, 2025) and by the diversity of designs and outcome reporting, which precluded a uniform quantitative synthesis. Nevertheless, the systematic PRISMA-guided approach and inclusion of multiple populations provide a broad cross-study overview of how VR is currently applied to EF training and what outcomes are most commonly observed.

Overall, confidence in the available evidence is limited by heterogeneity in VR protocols and EF outcome measures, small and diverse samples, and limited follow-up in many studies. Consequently, the findings should be interpreted cautiously, and future trials with larger samples, standardized EF measures, and longer follow-up are needed to strengthen confidence in the observed effects.

5.7. Recommendations for future research

To advance the field, future studies should prioritize: (i) domain-specific EF measurement (inhibition, shifting, updating/working memory, planning) alongside global cognition; (ii) rigorous designs with active controls matched for dose, engagement, and therapist contact; (iii) standardized reporting of VR dose (session frequency, duration, total exposure) and task demands; (iv) routine inclusion of follow-up assessments (e.g., 2–3 months, ideally longer) to characterize maintenance and decay; (v) evaluation of functional/ecological outcomes (instrumental activities of daily living, real-world multitasking, adherence, quality of life) to strengthen clinical relevance; and (vi) investigation of moderators (baseline EF severity, age, cybersickness/tolerability, motivation, immersion level) to clarify "what works for whom."

Future trials should consider adopting a standardized core EF battery covering inhibitory control, cognitive flexibility, working memory or updating, and planning or problem-solving. Where appropriate, this may include NIH Toolbox measures such as the Flanker Inhibitory Control and Attention Test, Dimensional Change Card Sort Test, and List Sorting Working Memory Test, supplemented by established neuropsychological measures such as the Stroop test, TMT-B, TOL, and Digit Span. Because assessment requirements differ across populations, this core battery should be complemented by population-specific measures and functional or participation outcomes. Additionally, comparative work is needed to determine when full immersion provides added value over well-designed non-immersive or semi-immersive systems, particularly given cost, accessibility, and usability considerations in clinical populations.

5.8. Qualitative effect size trends across virtual reality interventions

Across the included studies, reported effects of VR on executive cognitive outcomes were typically moderate, with occasional large effects emerging for specific executive indices, particularly when interventions were tightly aligned with EF demands (e.g., switching, inhibition, planning) and measured with domain-sensitive tests. In healthy/community samples and in older adults, several studies reported moderate effects on inhibition and shifting-related outcomes. For example, immersive VR exer-gaming produced moderate group × time effects after repeated training, whereas no effects were evident after a single session, indicating that effect magnitude increased with training dose rather than with immediate exposure.[99] In community-dwelling older adults, Makmee *et al.*[67] showed moderate to large interaction effects on EF components, including inhibition speed, updating indexed by FDS, and shifting accuracy, with null effects for more demanding active updating (BDS), suggesting that training may preferentially benefit less complex updating operations. Similarly, among older adults with MCI receiving VR cognitive–motor rehabilitation, between-group change effects ranged from small to large, with a moderate effect for improvement on TMT-B and a large effect for change in FDS, again supporting stronger effects for processing efficiency/attention–executive speed and simpler updating demands.[91]

In clinical neurological samples, effect sizes were more heterogeneous and often depended on the specificity of the executive metric. In TBI, De Luca *et al.*[3] reported a large between-group advantage for the executive switching control index at post-treatment, while other executive measures showed improvements that were less clearly differentiated from conventional training, indicating that the strongest effects clustered around flexible switching/integration demands. In Parkinson's disease/healthy aging, Fiorenzato *et al.*[2] reported consistent moderate effects for targeted EF related outcomes in the EF training arm, including group×time effects with Cohen's *d* values around 0.44–0.52 on key endpoints (e.g., inhibition related Stroop effects and other primary cognitive outcomes), with effects maintained at follow-up, suggesting a pattern of reliable but not uniformly large benefits when EF training is explicitly structured and adaptive.

In neuropsychiatric samples, available effect-size reporting also suggested mostly medium-range changes, although the design and sample size constrained interpretation. In schizophrenia/psychosis spectrum inpatients, Bisso *et al.*[97] observed significant improvement in frontal/EF on the FAB, while most other cognitive outcomes showed only trends and were attenuated after multiple comparison correction, consistent with a pattern of selective executive gains rather than broad cognitive change in a small trial. In a schizophrenia spectrum pilot using ecological VR cognitive remediation, Komemi *et al.*[96] reported medium to large effects for trained task engagement outcomes and medium effects for near transfer executive measures, suggesting that measurable executive improvements can emerge even within short programs, although causal inference is limited by non-randomized/single group methodology.

Overall, the qualitative trend indicates that VR interventions most often yield moderate executive benefits, with larger effects observed for specific executive control indices (particularly switching and targeted planning/inhibition outcomes) and when training is sufficiently dosed and measured with EF-sensitive instruments rather than global cognition alone.[67,99]

5.9. Ecological validity, cognitive overload, and the transfer problem

A central theoretical advantage of VR-based EF interventions is their potential ecological validity, that is, their capacity to approximate the perceptual, cognitive, and behavioral demands of everyday life more closely than traditional tabletop or decontextualized computerized tasks. Several included studies explicitly grounded training in daily life simulations (e.g., shopping, cooking, driving, and other instrumental activities), arguing that familiar contexts and interactive, multisensory engagement can increase motivation and participation, thereby enhancing cognitive outcomes. Increasing ecological realism can raise the risk of cognitive overload, particularly in populations with executive dysfunction, slow processing, fatigue, or sensory sensitivities. In cognitively vulnerable groups, highly immersive or complex multitasking scenarios might exceed cognitive resources, leading to reduced learning, more errors, or fatigue and cybersickness.

These considerations directly relate to the transfer problem, which examines whether improvements extend beyond the trained task to standard neuropsychological measures and, more importantly, to real-world functioning. The reviewed evidence indicates that VR often achieves strong on-task learning and, in some cases, near transfer to cognitively similar outcomes. However, far transfer to broader cognition and daily functioning is less consistently demonstrated and rarely measured comprehensively. Komemi *et al.*[96] explicitly assessed multiple "levels" of effectiveness (training engagement, near transfer, far transfer, and ecological transfer), reporting benefits not only in trained activities and standardized cognitive tests but also in increased participation diversity, an indicator of ecological transfer. They also emphasized that gaps often persist between cognitive improvements and functional changes and noted that the restrictive inpatient environment may limit the expression of improved capacity in real-world settings.

In contrast, studies that relied mainly on brief screening tools (e.g., global cognition measures) or omitted functional outcomes and follow-up make it difficult to determine whether observed EF improvements reflect generalized executive enhancement or context-specific performance gains. The significance of the "training dose" for transfer is also suggested by Huang[99], who found that executive benefits from immersive VR exergaming were not evident after a single session but emerged after four weeks of repeated training, indicating that lasting change may require sustained practice rather than brief exposure.

Overall, these findings suggest that VR can enhance ecological validity by integrating executive demands into realistic and engaging scenarios. However, it is important to balance this with the potential for overload, such as fatigue, cybersickness, or excessive cognitive load, that could reduce effectiveness in clinical groups. Moreover, the field still faces a persistent transfer challenge, particularly for far and ecological transfer, because functional, participation-level outcomes and long-term follow-up are infrequently included. Future VR EF trials would benefit from systematically manipulating and reporting cognitive load (e.g., adaptive difficulty, graded task complexity, distractor density), incorporating functional and participation outcomes alongside neuropsychological testing, and assessing whether transfer is maintained beyond the end of training.[2,96]

6. Conclusion

This systematic review synthesized data from 14 included studies identified through a PRISMA-guided review process, published between January 1, 2015, and December 31, 2025, examining VR interventions targeting EFs across neurological, neurodevelopmental, neuropsychiatric, and non-clinical populations. Overall, the findings present VR as a highly flexible and increasingly sophisticated platform for EF assessment and training. The interventions included non-immersive screen-based systems, semi-immersive or telerehabilitation solutions, and fully immersive

HMD environments. Regardless of immersion level, interventions commonly feature ecologically relevant, task-based simulations (such as daily-life or "supermarket" scenarios), serious games or exergames, and performance-linked feedback designed to mirror real-world executive demands. This approach may enhance motivation and adherence in clinical and educational settings.

Overall, the results indicate a generally positive pattern of EF improvement, with the most consistent and clear benefits observed in inhibitory control, cognitive flexibility/shifting, and planning/problem-solving. These areas seem especially responsive when VR training specifically targets these executive skills (e.g., interference control, rule switching, managing multistep goals) and when the assessments used are sensitive to EF changes (e.g., Stroop, Trail Making, TOL, frontal/executive batteries). Notably, several studies also found improvements in overall cognitive measures, implying that VR-based programs may support broader cognitive abilities, even when EF is not directly assessed. Collectively, these findings highlight the practical potential of VR as a scalable method for training specific executive skills within engaging, adaptable, and context-rich environments.

Regarding durability, the evidence is increasingly encouraging. While most studies relied on immediate post-intervention assessments, those that included follow-up measures suggest that VR-related improvements can last for weeks or months, indicating potential for meaningful long-term consolidation beyond short-term practice effects. Additionally, time-course patterns reported in the literature suggest that executive benefits tend to strengthen with repeated exposure across multi-week programs rather than after single sessions, supporting VR's role as a dose-responsive intervention format. These findings, along with the feasibility of remote delivery and therapist- or clinician-supervision on various platforms, position VR as a practical option for expanding access to EF training and rehabilitation, especially for individuals who need structured, engaging, and personalized practice.

Overall, this review shows that VR is more than just a new way to deliver content. It is a versatile and promising method for enhancing key aspects of executive control, such as inhibition, shifting, and planning, across various groups. Future studies should focus on larger, carefully controlled trials, use standardized tests that assess specific EF domains, include measures of functional and participation outcomes, and extend follow-up times to better understand long-term effects and real-world application. Determining the optimal combination of immersion level, task design, adaptivity, and dose for specific EF goals and populations will be important for optimizing VR interventions and supporting their appropriate integration into everyday education and clinical settings.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: Nikolaos Drakatos, Pantelis Pergantis, Athanasios Drigas

Data curation: Nikolaos Drakatos, Pantelis Pergantis, Andreas Petropoulos, Nikolaos Bardis, Nikolaos Doukas

Formal analysis: Nikolaos Drakatos, Pantelis Pergantis, Andreas Petropoulos, Nikolaos Bardis, Nikolaos Doukas

Investigation: Nikolaos Drakatos, Pantelis Pergantis, Andreas Petropoulos, Nikolaos Bardis, Nikolaos Doukas

Methodology: Nikolaos Drakatos, Pantelis Pergantis, Athanasios Drigas

Project administration: Nikolaos Drakatos, Pantelis Pergantis

Resources: Nikolaos Drakatos, Pantelis Pergantis, Athanasios Drigas

Supervision: Pantelis Pergantis, Athanasios Drigas

Validation: Pantelis Pergantis, Andreas Petropoulos, Nikolaos Bardis, Nikolaos Doukas, Athanasios Drigas

Visualization: Nikolaos Drakatos, Pantelis Pergantis

Writing–original draft: Nikolaos Drakatos, Pantelis Pergantis, Andreas Petropoulos, Nikolaos Bardis, Nikolaos Doukas

Writing–review & editing: All authors

All authors have read and agreed to the published version of the manuscript.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

References

1. Diamond A. Executive functions. *Annu Rev Psychol*. 2013;64:135-168.

   doi: 10.1146/annurev-psych-113011-143750

2. Fiorenzato E, Zabberoni S, De Simone MS, *et al*. Effects of virtual reality cognitive training on executive function and prospective memory in Parkinson's disease and healthy aging. *J Neurol Sci*. 2025;473:123507.

   doi: 10.1016/j.jns.2025.123507

3. De Luca R, Bonanno M, Marra A, *et al*. Can virtual reality cognitive rehabilitation improve executive functioning and coping strategies in traumatic brain injury? A pilot study. *Brain Sci*. 2023;13(4):578.

   doi: 10.3390/brainsci13040578

4. Tennant M, McGillivray J, Youssef GJ, McCarthy MC, Clark TJ. Feasibility, acceptability, and clinical implementation of an immersive virtual reality intervention to address psychological well-being in children and adolescents with cancer. *J Pediatr Oncol Nurs*. 2020;37(4):265-277.

   doi: 10.1177/1043454220917859

5. Cicerone KD, Goldin Y, Ganci K, *et al*. Evidence-based cognitive rehabilitation: systematic review of the literature from 2009 through 2014. *Arch Phys Med Rehabil*. 2019;100(8):1515-1533.

   doi: 10.1016/j.apmr.2019.02.011

6. Lee SA, Kim JY, Park JH. Concurrent validity of virtual reality-based assessment of executive function: A systematic review and meta-analysis. *J Intell*. 2024;12(11):108.

   doi: 10.3390/jintelligence12110108

7. Abulibdeh A, Zaidan E, Abulibdeh R. Navigating the confluence of artificial intelligence and education for sustainable development in the era of Industry 4.0: challenges, opportunities, and ethical dimensions. *J Clean Prod*. 2024;437:140527.

   doi: 10.1016/j.jclepro.2023.140527

8. Gkora V, Drigas A. Enhancing executive functions in children: a comprehensive review of interventions via digital technologies and future directions. *Sci Electron Arch*. 2024;17(5):1-11.

   doi: 10.36560/17520241974

9. Kontostavlou EZ, Drigas A. Executive functions training and giftedness. *Retos*. 2022;43:1005-1014.

   doi: 10.47197/retos.v43i0.90151

10. Sideraki A, Drigas AS. Neurocognitive training through VR and development of executive functions in individuals with autism spectrum disorder. *World J Adv Eng Technol Sci*. 2024;13(1):745-756.

    doi: 10.30574/wjaets.2024.13.1.0482

11. Drigas A, Karyotaki M. Attentional control and other executive functions. *Int J Emerg Technol Learn*. 2017;12(3):219-233.

    doi: 10.3991/ijet.v12i03.6587

12. Blair C. Educating executive function. *Wiley Interdiscip Rev Cogn Sci*. 2017;8(1-2):e1403.

    doi: 10.1002/wcs.1403

13. Meier C, Lea SEG, McLaren IPL. Measuring response inhibition with a continuous inhibitory-control task. *Learn Behav*. 2020;48(1):149-164.

    doi: 10.3758/s13420-019-00403-7

14. Drigas A, Sideraki A. Brain neuroplasticity leveraging virtual reality and brain-computer interface technologies: a systematic review. *Sensors*. 2024;24(17):5725.

    doi: 10.3390/s24175725

15. Botella C, Fernández-Álvarez J, Guillén V, García-Palacios A, Baños R. Recent progress in virtual reality exposure therapy for phobias: a systematic review. *Curr Psychiatry Rep*. 2017;19(7):42.

    doi: 10.1007/s11920-017-0788-4

16. Díaz-Pérez E, Flórez-Lozano JA. Virtual reality and dementia. *Rev Neurol*. 2018;66(10):344-352.

    doi: 10.33588/rn.6610.2017438

17. D'Cunha NM, Nguyen D, Naumovski N, *et al*. A mini-review of virtual reality-based interventions to promote well-being for people living with dementia and mild cognitive impairment. *Gerontology*. 2019;65(4):430-440.

    doi: 10.1159/000500040

18. Charles D, Holmes D, Charles T, McDonough S. Virtual reality design for stroke rehabilitation. *Adv Exp Med Biol*. 2020;1235:53-87.

    doi: 10.1007/978-3-030-37639-0_4

19. Thapa N, Park HJ, Yang JG, *et al*. The effect of a virtual reality-based intervention program on cognition in older adults with mild cognitive impairment: a randomized control trial. *J Clin Med*. 2020;9(5):1283.

    doi: 10.3390/jcm9051283

20. Pergantis P, Bamicha V, Chaidi I, Drigas A. Driving under cognitive control: the impact of executive functions in driving. *World Electr Veh J*. 2024;15(10):474.

    doi: 10.3390/wevj15100474

21. Slater M, Wilbur S. A framework for immersive virtual environments (FIVE): speculations on the role of presence in virtual environments. *Presence*. 1997;6(6):603-616.

    doi: 10.1162/pres.1997.6.6.603

22. Martirosov S, Bureš M, Zítka T. Cyber sickness in low-immersive, semi-immersive, and fully immersive virtual

reality. *Virtual Real*. 2022;26(1):15-32.

doi: 10.1007/s10055-021-00507-4

23. Mitsea E, Drigas A, Skianis C. Digitally assisted mindfulness in training self-regulation skills for sustainable mental health: a systematic review. *Behav Sci*. 2023;13(12):1008.

doi: 10.3390/bs13121008

24. Borgnis F, Baglio F, Pedroli E, *et al*. Available virtual reality-based tools for executive functions: a systematic review. *Front Psychol*. 2022;13:833136.

doi: 10.3389/fpsyg.2022.833136

25. Kirkham R, Kooijman L, Albertella L, Myles D, Yücel M, Rotaru K. Immersive virtual reality-based methods for assessing executive functioning: systematic review. *JMIR Serious Games*. 2024;12:e50282.

doi: 10.2196/50282

26. Maier M, Ballester BR, Leiva Bañuelos N, Duarte Oller E, Verschure P. Adaptive conjunctive cognitive training (ACCT) in virtual reality for chronic stroke patients: a randomized controlled pilot trial. *J Neuroeng Rehabil*. 2020;17(1):42.

doi: 10.1186/s12984-020-0652-3

27. Baggetta P, Alexander PA. Conceptualization and operationalization of executive function. *Mind Brain Educ*. 2016;10:10-33.

doi: 10.1111/mbe.12100

28. Doebel S. Rethinking executive function and its development. *Perspect Psychol Sci*. 2020;15(4):942-956.

doi: 10.1177/1745691620904771

29. Vugs B, Hendriks M, Cuperus J, Verhoeven L. Working memory performance and executive function behaviors in young children with SLI. *Res Dev Disabil*. 2014;35:62-74.

doi: 10.1016/j.ridd.2013.10.022

30. Kane MJ, Hambrick DZ, Tuholski SW, Wilhelm O, Payne TW, Engle RW. The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *J Exp Psychol Gen*. 2004;133(2):189-217.

doi: 10.1037/0096-3445.133.2.189

31. Drigas A, Karyotaki M. Executive functioning and problem solving: a bidirectional relation. *Int J Eng Pedagogy*. 2019;9(3):76-98.

doi: 10.3991/ijep.v9i3.10186

32. Posner MI, Petersen SE. The attention system of the human brain. *Annu Rev Neurosci*. 1990;13:25-42.

doi: 10.1146/annurev.ne.13.030190.000325

33. Mehsen V, Morag L, Chesta S, Cleaton K, Burgos H. Hot executive function assessment instruments in preschool children: a systematic review. *Int J Environ Res Public Health*. 2022;19(1):95.

doi: 10.3390/ijerph19010095

34. Meiran N. Reconfiguration of processing mode prior to task performance. *J Exp Psychol Learn Mem Cogn*. 1996;22(6):1423-1442.

doi: 10.1037/0278-7393.22.6.1423

35. Cristofori I, Cohen-Zimerman S, Grafman J. Executive functions. *Handb Clin Neurol*. 2019;163:197-219.

doi: 10.1016/B978-0-12-804281-6.00011-2

36. Funke J, Fischer A, Holt DV. Competencies for complexity: problem solving in the twenty-first century. In: Care E, Griffin P, Wilson M, eds. *Assessment and Teaching of 21st Century Skills: Research and Applications*. Springer; 2018:41-53.

doi: 10.1007/978-3-319-65368-6_3

37. Triegaardt J, Han TS, Sada C, Sharma S, Sharma P. The role of virtual reality on outcomes in rehabilitation of Parkinson's disease: meta-analysis and systematic review in 1,031 participants. *Neurol Sci*. 2020;41(3):529-536.

doi: 10.1007/s10072-019-04144-3

38. Zelazo PD. Executive function: reflection, iterative reprocessing, complexity, and the developing brain. *Dev Rev*. 2015;38:55-68.

doi: 10.1016/j.dr.2015.07.001

39. Drigas A, Mitsea E, Skianis C. Clinical hypnosis and VR, subconscious restructuring-brain rewiring and the entanglement with the 8 pillars of metacognition × 8 layers of consciousness × 8 intelligences. *Int J Online Biomed Eng*. 2022;18(1):78-95.

doi: 10.3991/ijoe.v18i01.26859

40. Chicchi Giglioli IA, Pallavicini F, Pedroli E, Serino S, Riva G. Augmented reality: a brand new challenge for the assessment and treatment of psychological disorders. *Comput Math Methods Med*. 2015;2015:862942.

doi: 10.1155/2015/862942

41. Freeman D, Reeve S, Robinson A, *et al*. Virtual reality in the assessment, understanding, and treatment of mental health disorders. *Psychol Med*. 2017;47(13):2393-2400.

doi: 10.1017/S003329171700040X

42. Rodríguez-Cano S, Delgado-Benito V, Ausín-Villaverde V, Martín LM. Design of a virtual reality software to promote the learning of students with dyslexia. *Sustainability*. 2021;13(15):8425.

doi: 10.3390/su13158425

43. Geraets CNW, Klein Tuente S, Lestestuiver BP, *et al*. Virtual reality facial emotion recognition in social environments: an eye-tracking study. *Internet Interv*. 2021;25:100432.

doi: 10.1016/j.invent.2021.100432

44. Bowman DA, Kruijff E, LaViola JJ, Poupyrev I. An introduction to 3-D user interface design. *Presence*. 2001;10(1):96-108.

doi: 10.1162/105474601750182342

45. Parsons TD, Gaggioli A, Riva G. Virtual reality for research in social neuroscience. *Brain Sci*. 2017;7(4):42.

doi: 10.3390/brainsci7040042

46. Velev D, Zlateva P. Virtual reality challenges in education and training. *Int J Learn Teach*. 2017;3(1):33-37.

doi: 10.18178/ijlt.3.1.33-37

47. Kamińska D, Sapiński T, Wiak S, *et al*. Virtual reality and its applications in education: survey. *Information*. 2019;10(10):318.

doi: 10.3390/info10100318

48. Jacoby M, Averbuch S, Sacher Y, Katz N, Weiss PL, Kizony R. Effectiveness of executive functions training within a virtual supermarket for adults with traumatic brain injury: a pilot study. *IEEE Trans Neural Syst Rehabil Eng*. 2013;21(2):182-190.

doi: 10.1109/TNSRE.2012.2235184

49. Morina N, Brinkman WP, Hartanto D, Kampmann IL, Emmelkamp PMG. Social interactions in virtual reality exposure therapy: a proof-of-concept pilot study. *Technol Health Care*. 2015;23(5):581-589.

doi: 10.3233/THC-151014

50. Parsons TD, Bowerly T, Buckwalter JG, Rizzo AA. A controlled clinical comparison of attention performance in children with ADHD in a virtual reality classroom compared with standard neuropsychological methods. *Child Neuropsychol*. 2007;13(4):363-381.

doi: 10.1080/13825580600943473

51. Rand D, Basha-Abu Rukan S, Weiss PLT, Katz N. Validation of the Virtual MET as an assessment tool for executive functions. *Neuropsychol Rehabil*. 2009;19(4):583-602.

doi: 10.1080/09602010802469074

52. Jensen L, Konradsen F. A review of the use of virtual reality head-mounted displays in education and training. *Educ Inf Technol*. 2018;23:1515-1529.

doi: 10.1007/s10639-017-9676-0

53. Germine L, Reinecke K, Chaytor NS. Digital neuropsychology: challenges and opportunities at the intersection of science and software. *Clin Neuropsychol*. 2019;33(2):271-286.

doi: 10.1080/13854046.2018.1535662

54. Parsons TD. Virtual reality for enhanced ecological validity and experimental control in the clinical, affective, and social neurosciences. *Front Hum Neurosci*. 2015;9:660.

doi: 10.3389/fnhum.2015.00660

55. Valmaggia LR, Latif L, Kempton MJ, Rus-Calafell M. Virtual reality in the psychological treatment for mental health problems: a systematic review of recent evidence. *Psychiatry Res*. 2016;236:189-195.

doi: 10.1016/j.psychres.2016.01.015

56. Ragan ED, Sowndararajan A, Kopper R, Bowman DA. The effects of higher levels of presence on procedure memorization performance and implications for educational virtual environments. *Presence*. 2010;19(6):527-543.

doi: 10.1162/pres_a_00016

57. McMahan RP, Bowman DA, Zielinski DJ, Brady RB. Evaluating display fidelity and interaction fidelity in a virtual reality game. *IEEE Trans Vis Comput Graph*. 2012;18(4):626-633.

doi: 10.1109/TVCG.2012.43

58. Saposnik G, Mamdani M, Bayley M, *et al*. Effectiveness of virtual reality exercises in stroke rehabilitation (EVREST): rationale, design, and protocol of a pilot randomized clinical trial assessing the Wii gaming system. *Int J Stroke*. 2010;5(1):47-51.

doi: 10.1111/j.1747-4949.2009.00404.x

59. McMahan RP, Alon AJD, Lazem S, *et al*. Evaluating natural interaction techniques in video games. In: Proceedings of the 2010 IEEE Symposium on 3D User Interfaces (3DUI); March 20-21, 2010; Waltham, MA. IEEE; 2010:11-14.

doi: 10.1109/3DUI.2010.5444727

60. Slater M. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philos Trans R Soc Lond B Biol Sci*. 2009;364(1535):3549-3557.

doi: 10.1098/rstb.2009.0138

61. Lessiter J, Freeman J, Keogh E, Davidoff J. A cross-media presence questionnaire: the ITC-Sense of Presence Inventory. *Presence*. 2001;10(3):282-297.

doi: 10.1162/105474601300343612

62. Tang A, Biocca F, Lim L. Comparing differences in presence during social interaction in augmented reality versus virtual reality environments: an exploratory study. In: Alcañiz Raya M, Rey Solaz B, eds. In: Proceedings of PRESENCE 2004: 7th Annual International Workshop on Presence; October 13-15, 2004; Valencia, Spain. Technical University of Valencia; 2004:204-208

63. Zelazo PD. Executive function and psychopathology: a neurodevelopmental perspective. *Annu Rev Clin Psychol*. 2020;16:431-454.

doi: 10.1146/annurev-clinpsy-072319-024242

64. Schmeichel BJ, Tang D. Individual differences in executive functioning and their relationship to emotional processes and responses. *Curr Dir Psychol Sci*. 2015;24:93-98.

doi: 10.1177/0963721414555178

65. Shen J, Xiang H, Luna J, *et al*. Virtual reality-based executive function rehabilitation system for children with traumatic brain injury: design and usability study. *JMIR Serious Games*. 2020;8(3):e16947.

doi: 10.2196/16947

66. Seesjärvi E, Laine M, Kasteenpohja K, Salmi J. Assessing goal-directed behavior in virtual reality with the neuropsychological task EPELI: children prefer head-mounted display but flat screen provides a viable performance measure for remote testing. *Front Virtual Real*. 2023;4:1138240.

doi: 10.3389/frvir.2023.1138240

67. Makmee P, Wongupparaj P. Virtual reality-based cognitive intervention for enhancing executive functions in community-dwelling older adults. *Psychosoc Interv*. 2022;31(3):133-144.

doi: 10.5093/pi2022a10

68. Kim DR, Lee S, Park J. Effect of individual virtual reality cognitive training programs on cognitive function and mood in middle-aged women: a randomized controlled trial. *JMIR Ment Health*. 2023;10:e48912.

doi: 10.2196/48912

69. Cummings JJ, Bailenson JN. How immersive is enough? A meta-analysis of the effect of immersive technology on user presence. *Media Psychol*. 2016;19(2):272-309.

doi: 10.1080/15213269.2015.1015740

70. Witmer BG, Singer MJ. Measuring presence in virtual environments: a presence questionnaire. *Presence*. 1998;7(3):225-240.

doi: 10.1162/105474698565686

71. Makransky G, Terkildsen TS, Mayer RE. Adding immersive virtual reality to a science lab simulation causes more presence but less learning. *Learn Instr*. 2019;60:225-236.

doi: 10.1016/j.learninstruc.2017.12.007

72. Smith SA, Mulligan NW. Immersion, presence, and episodic memory in virtual reality environments. *Memory*. 2021;29(8):983-1005.

doi: 10.1080/09658211.2021.1953535

73. De Lillo M, Brunsdon VEA, Bradford EEF, Gasking F, Ferguson HJ. Training executive functions using an adaptive procedure over 21 days (10 training sessions) and an active control group. *Q J Exp Psychol*. 2021;74(9):1579-1594.

doi: 10.1177/17470218211002509

74. Cutillo G, Brazzoduro V, Bedogni G, *et al*. Executive functions rehabilitation in premature children using an adaptive motion-interaction videogame platform: a randomized controlled trial. *Games Health J*. 2024;13(5):346-353.

doi: 10.1089/g4h.2023.0078

75. Faria AL, Andrade A, Soares L, Bermúdez i Badia S. Benefits of virtual reality-based cognitive rehabilitation through simulated activities of daily living: a randomized controlled trial with stroke patients. *J Neuroeng Rehabil*. 2016;13:96.

doi: 10.1186/s12984-016-0204-z

76. Slater M, Spanlang B, Sanchez-Vives MV, Blanke O. First-person experience of body transfer in virtual reality. *PLoS ONE*. 2010;5(5):e10564.

doi: 10.1371/journal.pone.0010564.

77. Maselli A, Slater M. The building blocks of the full-body ownership illusion. *Front Hum Neurosci*. 2013;7:83.

doi: 10.3389/fnhum.2013.00083

78. Banakou D, Groten R, Slater M. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proc Natl Acad Sci USA*. 2013;110(31):12846-12851.

doi: 10.1073/pnas.1306779110

79. Jovanovski D, Zakzanis K, Campbell Z, Erb S, Nussbaum D. Development of a novel, ecologically oriented virtual reality measure of executive function: the Multitasking in the City Test. *Appl Neuropsychol Adult*. 2012;19(3):171-182.

doi: 10.1080/09084282.2011.643955

80. Jovanovski D, Zakzanis K, Ruttan L, Campbell Z, Erb S, Nussbaum D. Ecologically valid assessment of executive dysfunction using a novel virtual reality task in patients with acquired brain injury. *Appl Neuropsychol Adult*. 2012;19(3):207-220.

doi: 10.1080/09084282.2011.643956

81. Josman N, Elbaz Schenirderman A, Klinger E, Shevil E. Using virtual reality to evaluate executive functioning among persons with schizophrenia: a validity study. *Schizophr Res*. 2009;115(2-3):270-277.

doi: 10.1016/j.schres.2009.09.015

82. Park JH. Does the virtual shopping training improve executive function and instrumental activities of daily living of patients with mild cognitive impairment? *Asian J Psychiatr*. 2022;69:102977.

doi: 10.1016/j.ajp.2021.102977

83. Liao YY, Tseng HY, Lin YJ, Wang CJ, Hsu WC. Using virtual reality-based training to improve cognitive function, instrumental activities of daily living and neural efficiency in older adults with mild cognitive impairment. *Eur J Phys Rehabil Med*. 2020;56(1):47-57.

doi: 10.23736/S1973-9087.19.05899-4

84. Baddeley A. Working memory: theories, models, and controversies. *Annu Rev Psychol*. 2012;63:1-29.

doi: 10.1146/annurev-psych-120710-100422

85. Kueider AM, Parisi JM, Gross AL, Rebok GW. Computerized cognitive training with older adults: a systematic review. *PLoS ONE*. 2012;7(7):e40588.

doi: 10.1371/journal.pone.0040588

86. Rizzo AS, Koenig ST. Is clinical virtual reality ready for primetime? *Neuropsychology*. 2017;31(8):877-899.

doi: 10.1037/neu0000405

87. Schultheis MT, Rizzo AA. The application of virtual reality technology in rehabilitation. *Rehabil Psychol*. 2001;46(3):296-311.

doi: 10.1037/0090-5550.46.3.296

88. Lohse KR, Hilderman CG, Cheung KL, Tatla S, Van der Loos HF. Virtual reality therapy for adults post-stroke: a systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PLoS ONE*. 2014;9(3):e93318.

doi: 10.1371/journal.pone.0093318

89. Mitsea E, Drigas A, Skianis C. Virtual reality and metacognition training techniques for learning disabilities. *Sustainability*. 2022;14(16):10170.

doi: 10.3390/su141610170

90. Sheehan WA, Iarocci G. Executive functioning predicts academic but not social adjustment to university. *J Atten Disord*. 2019;23(16):1792-1800.

doi: 10.1177/1087054715612258

91. Park JS, Jung YJ, Lee G. Virtual reality-based cognitive-motor rehabilitation in older adults with mild cognitive impairment: a randomized controlled study on motivation and cognitive function. *Healthcare*. 2020;8(3):335.

doi: 10.3390/healthcare8030335

92. Maggio MG, Bonanno L, Rizzo A, *et al*. The role of virtual reality-based cognitive training in enhancing motivation and cognitive functions in individuals with chronic stroke. *Sci Rep*. 2025;15(1):25258.

doi: 10.1038/s41598-025-08173-1

93. Maggio MG, Rizzo A, Benenati A, *et al*. Efficacy and feasibility of virtual reality-based cognitive telerehabilitation in Parkinson's disease: a pilot randomized controlled trial on patients and caregivers. *Digit Health*. 2025;11:20552076251376534.

doi: 10.1177/20552076251376534

94. Park JH, Liao Y, Kim DR, *et al*. Feasibility and tolerability of a culture-based virtual reality training program in patients with mild cognitive impairment: a randomized controlled pilot study. *Int J Environ Res Public Health*. 2020;17(9):3030.

doi: 10.3390/ijerph17093030

95. Zaragoza-Mezquita M, Felix-Esbrí S, Sebastián-Tirado A, *et al*. Exploring the potential of immersive virtual reality as a tool to enhance cognitive functions and alleviate clinical symptoms in multiple sclerosis. *Mult Scler Relat Disord*. 2025;93:106235.

doi: 10.1016/j.msard.2024.106235

96. Komemi R, Tubenbaltt H, Harel EV, Nahum M, Lipskaya-Velikovsky L. Ecological virtual reality-based cognitive remediation among inpatients with schizophrenia: a pilot study. *Schizophr Res Cogn*. 2024;38:100326.

doi: 10.1016/j.scog.2024.100326

97. Bisso E, Caponnetto P, Auditore R, *et al*. Treatment of cognitive deficits in schizophrenia using a new technique of cognitive training in virtual reality: a pilot study. *Health Psychol Res*. 2025;13:129550.

doi: 10.52965/001c.129550

98. Schena A, Garotti R, D'Alise D, *et al*. IAmHero: preliminary findings of an experimental study to evaluate the statistical significance of an intervention for ADHD conducted through the use of serious games in virtual reality. *Int J Environ Res Public Health*. 2023;20(4):3414.

doi: 10.3390/ijerph20043414

99. Huang K. Exergaming executive functions: an immersive virtual reality-based cognitive training for adults aged 50 and older. *Cyberpsychol Behav Soc Netw*. 2020;23(3):143-149.

doi: 10.1089/cyber.2019.0269

Appendix

Exact reproducible search strings (as executed) are reported below by database:

The searches were based on two concept blocks: (i) virtual-reality-related terms and (ii) executive-function-related terms. Terms within each block were combined with OR, and the two blocks were combined with AND. The following strategies preserve the searches reported in the manuscript, while correcting line breaks and formatting abnormalities.

PubMed/MEDLINE

Search fields: Title/Abstract and controlled vocabulary (MeSH)

Filters applied: English; Journal Article; publication date from January 1, 2015, to December 31, 2025

Date searched: January 12, 2026

Exact search query:

```
(
  "Virtual Reality"[Mesh]
  OR "virtual reality"[Title/Abstract]
  OR VR[Title/Abstract]
  OR "immersive virtual reality"[Title/Abstract]
  OR "virtual environment"[Title/Abstract]
  OR "head mounted display"[Title/Abstract]
  OR HMD[Title/Abstract]
  OR "360 video"[Title/Abstract]
  OR "serious game"[Title/Abstract]
)
AND
(
  "Executive Function"[Mesh]
  OR "executive function"[Title/Abstract]
  OR "inhibitory control"[Title/Abstract]
  OR "working memory"[Title/Abstract]
  OR planning[Title/Abstract]
  OR "attentional control"[Title/Abstract]
  OR "problem solving"[Title/Abstract]
  OR "cognitive control"[Title/Abstract]
)
```

The following filters were applied through the PubMed interface:

Publication date: January 1, 2015–December 31, 2025
Language: English
Article type: Journal Article
Web of Science Core Collection

Search field: Topic, including title, abstract, author keywords, and Keywords Plus
Filters applied: Publication years 2015–2025; English; Article
Date searched: January 12, 2026

Exact search query:

```
TS=(
 (
  "virtual reality"
  OR VR
  OR "immersive virtual reality"
  OR "virtual environment"
  OR "head mounted display"
  OR HMD
  OR "360 video"
  OR "serious game"
 )
 AND
 (
  "executive function"
  OR "inhibitory control"
  OR "working memory"
  OR planning
  OR "attentional control"
  OR "problem solving"
  OR "cognitive control"
 )
)
```

The following filters were applied through the Web of Science interface:

Timespan: 2015–2025
Language: English
Document type: Article
Scopus

Search fields: Title, abstract, and keywords
Filters applied: Publication years 2015–2025; English; Article
Date searched: January 12, 2026

Exact search query:

```
TITLE-ABS-KEY(
 (
  "virtual reality"
  OR VR
  OR "immersive virtual reality"
  OR "virtual environment"
  OR "head mounted display"
  OR HMD
  OR "360 video"
  OR "serious game"
 )
 AND
 (
  "executive function"
  OR "inhibitory control"
  OR "working memory"
  OR planning
  OR "attentional control"
  OR "problem solving"
  OR "cognitive control"
 )
)
AND PUBYEAR > 2014
AND PUBYEAR < 2026
```

AND LIMIT-TO(LANGUAGE, “English”)

AND LIMIT-TO(DOCTYPE, “ar”)

This is the clean version of the Scopus strategy already reported in the manuscript.

Google Scholar

Search mode: Articles

Restrictions applied: Custom publication range 2015–2025; English-language and journal-article eligibility verified during screening

Date searched: January 12, 2026

Exact search query:

```
(
 “virtual reality”
 OR VR
 OR “immersive virtual reality”
 OR “virtual environment”
 OR “head mounted display”
 OR HMD
 OR “360 video”
 OR “serious game”
)
AND
(
 “executive function”
 OR “inhibitory control”
 OR “working memory”
 OR planning
 OR “attentional control”
 OR “problem solving”
 OR “cognitive control”
)
```

The custom year range 2015–2025 was applied within Google Scholar. English language, publication type, and eligibility were subsequently confirmed during title/abstract and full-text screening, as already described in the manuscript.

Searches were conducted on January 12, 2026. The search strategies comprised two concept blocks: virtual-reality-related terms and executive-function-related terms. Terms within each block were combined using OR, and the two blocks were

combined using AND. Database-specific fields, controlled vocabulary, publication-year restrictions, language limits, and document-type filters were applied as reported above.