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Artificial Cognitive Systems Applied in Executive Function Stimulation and Rehabilitation Programs: A Systematic Review

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Abstract

This article presents a systematic review of studies on cognitive training programs based on artificial cognitive systems and digital technologies and their effect on executive functions. The aim has been to identify which populations have been studied, the characteristics of the implemented programs, the types of implemented cognitive systems and digital technologies, the evaluated executive functions, and the key findings of these studies. The review has been carried out following the PRISMA protocol; five databases have been selected from which 1889 records were extracted. The articles were filtered following established criteria, to give a final selection of 264 articles that have been used for the purposes of this study in the analysis phase. The findings showed that the most studied populations were school-age children and the elderly. The most studied executive functions were working memory and attentional processes, followed by inhibitory control and processing speed. Many programs were commercial, customizable, gamified, and based on classic tasks. Some more recent initiatives have begun to incorporate user-machine interfaces, robotics, and virtual reality, although studies on their effects remain scarce. The studies recognize multiple benefits of computerized neuropsychological stimulation and rehabilitation programs for executive functions in different age groups, but there is a lack of studies in specific population sectors and with more rigorous research designs.

Keywords Computrized cognitive training · Artificial cognitive systems · Executive functions · Systematic review

1 Introduction

The digital technological advances of the last decades have driven significant transformations in health services for all populations, including neuropsychological care programs. Currently, it is recognized that many rehabilitation and cognitive stimulation programs have incorporated digital technologies and artificial cognitive systems [1–11]. These programs, in general, have promoted new lines of action toward understanding and capitalizing on the human–computer interaction at the service of the neuropsychological health.

Multiple perspectives have been developed for the incorporation of digital technologies and cognitive systems in

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rehabilitation and neurocognitive stimulation, such as serious games for health, digital mental health interventions, computer training based on restitution, apps based on the brain-computer interface, virtual reality cognitive training, rehabilitation software, among others. In general, in this systematic review, the programs have been grouped under the concept of computer-based cognitive training (hereinafter referred to as CCT), and we were particularly interested in the rehabilitation and stimulation of executive functions.

1.1 Executive Functions

The term "executive functions" (hereinafter referred to as EFs) refer to a diversity of cognitive hypotheses of processes carried out by prefrontal areas of the brain [12]. They refer to a series of neurological functions and higher-order cognitive abilities that allow for the sophisticated processing of input information, making it possible to plan, organize, guide, review, flexible, regularize, and evaluate the behavior to achieve goals. In conclusion, they constitute critical cognitive control mechanisms to self-regulate future-oriented behavior and adapt to the changing demands of the environment [13].

Currently, there are multiple theoretical models from which this construct is conceptualized, and each investigation takes the side of the one that best fits its epistemological current. Some models contemplate this process in a unified way, under executive function, central executive, executive control, or cognitive functioning [14–16], referring to regulating, coordinating, and directing cognitive, affective, and behavioral processes. Other theoretical models implement the concept of executive functions pluralistically and discriminate between a series of higher-order cognitive processes that have an intimate interaction with each other and with the most basic cognitive processes [17–19]. The classification of executive functions does not enjoy consensus in the academic community either; Goldstein [12] recognizes at least 30 classifications, making this concept difficult to define operationally. However, there is general agreement concerning three central nuclei of EFs: inhibitory control, working memory, and cognitive flexibility, following the hierarchical model proposed by Miyake [17]. The above central nuclei emerge from others of a higher order, such as reasoning, problem solving, and planning.

1.2 Cognitive Computational Training

Neuropsychological intervention programs can be divided into two branches: stimulation and rehabilitation [20]. Rehabilitation is focused on people who have lost a certain level of performance in their executive functioning, either due to a neurodevelopmental condition, acquired neurological damage, neurological deterioration, or as a consequence of a pathology. Rehabilitation seeks to reestablish the subject's situation to the highest possible level of functioning [21], under the principles of restitution, compensation, and substitution [22]. Cognitive stimulation, for its part, seeks to establish new learning under the premise that the subject has not acquired it yet. Therefore, it seeks to contribute to the occurrence of transformations in the nervous system facilitated by its neuroplasticity [20]. Stimulation comprises activities to improve general cognitive performance or some of its cognitive processes in particular [23] based on principles of transfer and generalization. For this research, both types of rehabilitation and stimulation programs will be grouped under "cognitive training."

The literature on the subject suggests that clinical trials and other types of cognitive training studies should design or select training programs based on solid theoretical references and start from a neuropsychological evaluation exercise. It also highlights the need for intervention schemes to be process-oriented rather than task training [24]. This allows for a near-transfer effect (improvement in untrained tasks that measure the same cognitive component) and far transfer effect (improvement in untrained tasks that measure related cognitive components).

Currently, studies seek to advance to programs that, in addition to improving target cognitive processes, improve their neurological bases, by producing reorganization in brain structure and functioning [20]. For this reason, other measurement options have begun to be incorporated in addition to standardized neuropsychological values, including neuroimaging alternatives such as functional magnetic resonance imaging, event-related potentials, and an electroencephalogram. The findings on the overall effects of training and transfer provide researchers with new possibilities for the application of their findings, beyond clinical settings, to similar situations such as education [25].

One of the first initiatives to use computer systems in cognitive training programs has been the digitization of activities that were classically carried out through pencil and paper exercises [26, 27]. Also, there has been a rise in the gamification of activities, which has had such positive results that it paved the way for the creation of serious games, specifically designed for clinical or educational purposes [28–30].

Regarding the neurorehabilitation and stimulation of executive functions, nowadays, it is possible to find numerous computerized cognitive training programs that use software, applications, and online platforms. These programs offer significant advantages to health professionals, including having an extensive repository of activities, providing tools for planning sessions, designing personalized programs, providing feedback to the participant, and monitoring the patient's progress. On the other hand, the use of machine learning algorithms has optimized data processing and collection and has made possible the adaptation of activities to the needs and progress of each patient [31, 32].

Another benefit of the CCT is access to programs from multiple devices, such as computers, tablets, and smartphones; this has improved affordability for patients and has made it possible to overcome logistical and geographical limitations; the advantages of multidevice access have become evident during the health emergency caused by COVID-19 [5, 6]. The biosafety measures that implemented to counteract the pandemic, such as social distancing and lockdown, and the lack of availability of mental health professionals, have formulated new challenges to neuropsychological care programs. Digital technologies have provided alternative solutions to these challenges, which has led them to grow in popularity.

Among other technological innovations in cognitive training programs, it is possible to find the design of augmented reality and virtual reality resources [33–36], the incorporation of robotic devices [5, 32, 37], the design of new devices and interventions that integrate brain-computer interfaces, such as neurofeedback [10, 30, 38], as well as new high-tech interventions such as transcranial direct current stimulation [39, 40].

In response to this phenomenon, there has been an increase in the studies evaluating the feasibility, adherence, and effects of computerized cognitive training programs on executive functions [9, 41–43]. However, despite the potential of these programs, there have been repeated inconsistencies in the findings of the systematic reviews of clinical trials in this area [25, 44].

Concerning the target populations of the programs, some findings restrict their effectiveness to early ages or older adults [45]. However, other studies position these technologies among the new means of cognitive training which help achieve long-lasting, although with different degrees of efficiency [25]. Some recent systematic reviews and meta-analyses have compiled clinical trials and experimental studies to account for the effects of different computer-based cognitive training programs. Three systematic reviews compiled more than 101 randomized clinical trials (from now on RCTs) in children with ADHD that implemented different CCT modalities such as serious games, virtual reality, and neurofeedback [7, 46, 47]; a large part of these interventions demonstrated a favorable effect on executive functions such as working memory, attention, planning, inhibition and self-regulation.

A systematic review of gamification-based digital mental health interventions [8] identified favorable effects on executive functioning in children with other neurodevelopmental disorders, with other benefits in terms of engagement, usability, and mental health gap reduction. Another review that compiled the effects of programs based on brain-computer interface devices [30] found a positive impact on EFs of attention and working memory, as well as on visuospatial, social, and emotional skills of children with neurodevelopmental disorders such as autism and ADHD.

A systematic review of 19 RCTs in children and adolescents with autism found that, in general, the implementation of CCT shows more significant improvements in executive functions compared to treatment as usual, with carry-over effects on social skills [44]; however, these interventions in children with intellectual disabilities have been poorly studied [48]. In children with typical neurodevelopment, a systematic review of 16 RCTs found that CCTs demonstrated effects of near transfer to working memory and far transfer to inhibitory control and attention [49]. Meanwhile, another review of 15 studies found that, in general, the transfer effects of these programs to executive functions are limited [50].

Regarding the adult population, a systematic review compiled nine studies that evaluated the effects of a CCT based on virtual reality in patients with various neuropsychological disorders; the authors found improvements in executive function and attention associated with the intervention, with effects on motivation and adherence to treatment [51]. In adults with depression, a meta-analysis including nine studies [3] found that CCTs had moderate to strong effects on WM, attention, and global cognitive functioning while reducing depressive symptoms.

Some systematic reviews of computer-based cognitive remediation programs in adults with schizophrenia have been shown to have favorable effects on working memory and social cognition [52], while other reviews in this population did not acknowledge conclusive results [2]. CCTs have also been shown to be feasible for strengthening executive functioning in healthy adults, also proving to be easily incorporated in the workplace [53].

The elderly population has also been one of the age groups in which CCTs have been most investigated to prevent or delay cognitive deterioration in neurodegenerative disorders associated with aging. However, some reviews have found a lack of interdisciplinary consensus and instead there is a continuous debate about the benefits of these programs [25, 54], as well as a lack of consensus when defining a taxology of the cognitive domains studied [9].

A systematic review of 20 studies in healthy older adults found that much of the evaluated CCT effects were limited to trained or near-transfer tasks. However, other studies incorporating diagnostic imaging found structural improvements evidenced by cortical and gray matter increases, changes in subcortical and frontal activation after training; the authors concluded that executive function training with CCT may reduce dependence on compensatory neural mechanisms [53].

In patients with acquired brain injury, a review of 23 studies reported significant improvements in attention and executive function following training [1]. In older adults with depression, a meta-analysis [55] found that commercial virtual reality games improved cognitive function, memory and decreased depressive symptoms.

In adults with mild cognitive impairment, a review of 22 studies found significant effects on global cognitive function, attention, executive function, and memory [55]. Another review in this population [35] assessed the efficacy of 16 computer-based and virtual reality programs, with most studies showing improvements in attention, executive function, and visual and verbal memory. Both reviews found that these interventions also decrease symptoms of depression and anxiety. A meta-analysis of 16 RCT trials looked at CCT programs that incorporated serious games in older adults with cognitive impairment, most of these demonstrating significant improvement in cognitive function [11].

In older adults with a history of stroke, a meta-analysis reviewed the effect of virtual reality rehabilitation from 21 studies, which demonstrated improvements in executive functions and changes in evoked potentials that showed a positive effect of the intervention [36]. Other reviews recognized transfer effects on working memory [4], attention and executive functions, and neural changes in both functional and structural connectivity in brain areas related to executive functioning [45]; however, both reviews noted that the results were very heterogeneous between studies [4, 45].

A large part of the systematic reviews found limitations in these studies associated with the lack of methodological rigor, the lack of blinding of the participants and evaluators, diversity in the measurement instruments, and poor replication of the intervention protocols [7, 25, 35, 44–48, 51]. Variability in designs, instruments, and protocols limited the performance of other meta-analyses [11, 35, 45]. Some authors point out that the results of the studies should be taken with moderation and could require new researches [11, 45, 51]. Other authors also warn of the limitations to the application of these programs, especially in developing countries, such as the lack of technological infrastructure, access to quality networks, and sociocultural adaptability [8].

The systematic reviews and meta-analyses carried out to date on this topic have provided a general overview of the benefits and limitations of incorporating digital technologies and artificial cognitive systems into rehabilitation and neuropsychological stimulation programs in different populations. However, the effects that CCTs have shown on executive functions have been so diverse that they cannot be conclusive. To date, studies that analyze the differences in use and scope of this type of intervention according to the group population and age range have not been found.

With the current systematic review, a systematic compilation of the experimental and quasi-experimental studies in which the use of the CCT has been evaluated in different populations and clinical groups was carried out in order to provide an overview of the current state of the studies on the topic and to account for the populations that have been studied, the type of the implemented digital technologies and artificial cognitive systems, the characteristics of the interventions, the studied executive functions, and the most significant effects. Besides, an assessment has been made of the main benefits of the use of artificial intelligence and computational systems in neuropsychological intervention programs, and challenges to be addressed in the future, have been identified.

2 Methods

The systematic review (SR) research methodology aims to collect, evaluate, and analyze representative studies in a specific field of knowledge. It aims to provide a clear and structured summary of information in response to a specific question [56]. Although SRs have been initially used in health sciences to try to answer questions related to treatment, diagnosis, or prognosis [57], their validity is currently recognized in other areas of knowledge such as engineering [58]. SRs have a rigorous methodology that includes structuring a straightforward question, systematic and exhaustive search of all potentially relevant articles, selection by explicit and reproducible criteria of articles to be included, the description of the design and execution of the original studies, the synthesis of the obtained data and the interpretation of the results [56]. The systematic review protocol PRISMA-Preferred Reporting Items for Systematic reviews and Meta-Analyzes [59], proposed by Cochrane Collaboration [57, 60], has been followed in the present study.

2.1 Research Question Formulation

The purpose of this systematic review has been to identify the studies that have been carried out in the last five years on cognitive training programs for EFs based on digital technologies. By examining the use of artificial cognitive systems applied in programs for the stimulation and rehabilitation of executive cognitive processes, the study contributes to state of the art and distinguishes the populations, contexts, type of technologies, uses, and characteristics of said programs. The PICO model proposed by the Cochrane Collaboration was implemented to consolidate the review question [61]. This model plans that the question should be focused on four aspects: the patient or the problem being treated (P), the intervention or exposure being considered (I), the intervention comparison, when relevant (C) and clinical outcomes of interest (O) (see Table 1).

One of the purposes of the PICO model is to define the general concepts or theoretical categories of work that act as axes on which the review is structured and that are, therefore, critical when defining the research questions. These theoretical

Table 1 Definition of concepts using PICO

ID	Concepts
Population	Healthy population, clinical population, different age groups
Intervention	Cognitive training programs based on digital technologies to stimulate, train or rehabilitate executive functions
Comparison	Non-computerized training programs
Outcomes	Effects of the intervention, feasibility, characteristics of the cognitive training program, executive functions programs studied

Table 2 Research questions for the systematic review

ID	Research question
RQ1	What is the current status of studies on the effects of CCTs on executive functions?
RQ2	What are the population groups in which CCTs have been investigated?
RQ3	Which EFs showed significative effects after the application of CCTs?
RQ4	What are the characteristics of CCTs studied?
RQ5	What are the effects on the EF shown by the CCT and their differences by age group?

categories of work are: (1) Executive Function; (2) Computarized Cognitive Training. The research questions guiding the systematic review were formulated from the PICO analysis (Table 2).

2.2 Definition of the Inclusion and Exclusion Criteria

For this study, the researchers selected the following interdisciplinary databases: Science Direct (DB1), Scopus (DB2), ProQuest (DB3), Springer (DB4), and PubMed (DB5). The criteria for selecting or rejecting the articles to be included in the systematic review were: (1) articles published in the selected databases; (2) articles that present results of clinical trials, experimental studies, quasi-experimental studies; (3) the studies that evaluate the effect of a CCT on the executive functions of a group of subjects; (4) documents published from 2015 to the date of execution of the search (July 2021). The established exclusion criteria were: (1) short articles that do not present either results, protocols, meta-analyses, or systematic reviews; (2) studies on cognitive training programs that are not based on computer systems; and (3) studies not assessing executive functions.

2.3 Search Strategy Execution

On the basis of the research questions, the terms mainly used in the literature on the subject were established as the keywords with which the search string was built. These keywords were collated in two thesauri: ERIC, a tool for standardized terms in education and health, and IEEE, which provides a controlled vocabulary for the engineering area. Once the appropriate keywords had been selected for the search, several complete query strings were built, complemented with logical operators. The syntax had to be modified to adapt to the particularities of each database (See "Appendix A").

"Executive function" OR "executive functions" AND "cognitive training" OR "cognitive rehabilitation" AND Computerized OR "Based-computer"

In order to analyze the most recent results, the search was limited to articles published from 2015 to the present (cut-off date July 2020).

2.4 Study Selection and Filter Application

The execution of the search strings yielded a total of 1889 records distributed in the different databases. Once the search string was executed, the articles were reviewed on the basis of the criteria defined for their search. After filtering the title, abstract and full text, in the final phase of the review, 264 articles were selected for analysis. The flow diagram, PRISMA [59], presented in Fig. 1 describes the procedure carried out throughout the different phases of the systematic review.

3 Results

RQ1 What is the current status of studies on the effects of CCTs on executive functions?

Although the review only included articles reviewed in the last 5 years, sustained increase has been evident over the last decade, which is a reflection of the great acceptability of CCTs.

According to the georeferencing of the studies (Fig. 2), 46.6% were carried out in Europe, distributed in 22 countries of the continent, where Spain stood out, with 7.6% of the total studies, followed by Italy and Germany with 5.7%, respectively. 37.9% of the studies has been carried out in America, 30.7% belonged to the United States, while out of the remaining 7.2%, only 2.7% took place in South America. Asia has 12.5%, of which 4.9% were carried out in China. In lower percentages, studies were also found in Oceania (4.9%) and Africa (0.8%).

All the studies included in the final sample had an experimental or quasi-experimental methodological design. 18.2% corresponded to preliminary studies such as pilot, exploratory, feasibility studies, and proofs of concept, while 81.8% were intervention studies; the majority were randomized controlled trials, some were clinical superiority trials, and non-randomized controlled trials single group,

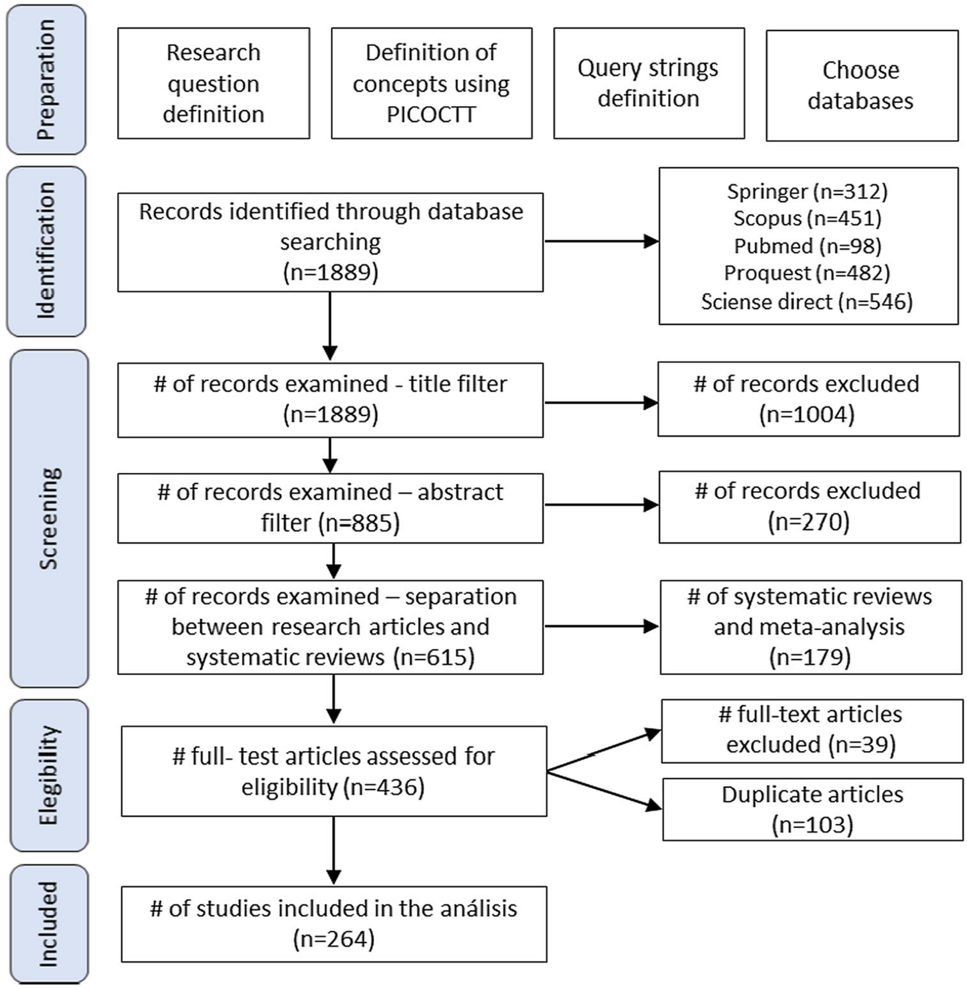

Fig. 1 Flowchart of the phases of the systematic review

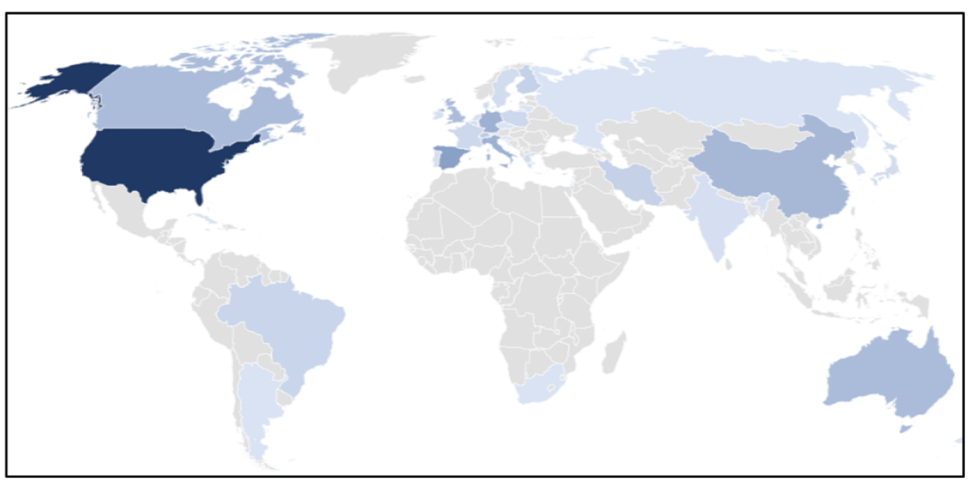

Fig. 2 World map and graph with the georeferencing of the studies

or crossover diagnostic trials. All studies included at least two measurement cuts in pre and post-tests, but only 26.9% included post-test follow-up tests. 89% of the studies were controlled, 58.8% had a two-group design (training group and control group), 21.2% had three groups, 8.3% had four, and 2.3% had more than five. 56.6% implemented active control groups, 34% passive controls, and 9.4% included at least one passive and one active control group. Group allocation was random in most studies (82.9%), and in the minority were pseudo-random (1.5%) or by convenience (2.3%) (Table 3).

The participants' mean number was 37.3 in the preliminary studies and 89.6 in the intervention studies. When

Table 3 Characteristics of the methodological designs of the studies

Characteristics of the studies			
N = 264 Frequency (%)			
Type of study		*Control group*	
Preliminary	48 (18.2)	Controlled	235 (89)
Intervention	216 (81.8)	No controlled	29 (11)
Allocation		*Type of group control*	
Random	218 (82.6)	Active	133 (56.6)
Pseudo-random	4 (1.5)	Passive	22 (9.4)
Not random	36 (13.6)	Active y passive	80 (34)
Not specified	6 (2.3)		
Tracing		*Group numbers*	
With tracing	73 (26.9)	Mean (Median)	2.4 (2)
Without tracing	193 (73.1)	SD (P25-P75)	0.9 (2–3)

N Number, *SD* standard deviation, *P25* percentile 25, *P75* percentile 75

Table 4 Sample size and study groups

	Preliminary N = 48	Intervention N = 214	Total N = 262
Sample size			
Mean (Median)	37.3 (30)	89.6 (65.5)	80.1 (57)
SD (P25-P75)	24.7 (20–49.7)	89.4 (37.7–99)	83.9 (32–91)
Group size			
Mean (Median)	20.5 (18)	38 (28)	34.82 (26)
SD (P25-P75)	12.3 (11–27)	40.3 (19–41.2)	37.3 (17–39.5)

N Number, *SD* standard deviation

analyzing the distribution by percentiles, 75% of the preliminary studies had a sample less than 49.7 and in the intervention studies less than 99 subjects (Table 4). The mean group size also varied depending on whether the study was preliminary (20.5) or whether it was an intervention.

RQ2 What are the population groups in which CCTs have been investigated?

The results showed that 59.1% of the studies were carried out in the clinical population and 40.9 in the healthy population. However, this proportion varied when crossing this variable with the age group. In Table 5 and Fig. 3, descriptive statistics of the total of the studies are presented by age groups, and it is distinguished how many were carried out on a population with a clinical diagnosis and involved healthy subjects.

In the general sample, a higher frequency of jobs was observed in older adults (29.2%) and school-age children (26.9%). Most of the investigations carried out with older adults, middle adults, and preschoolers regarded clinical populations, while those that involved school children, adolescents, and young adults were carried out on healthy populations.

Figure 3 shows the clinical conditions in which the effects of ACS-based EF cognitive training programs have been most studied.

In school-age and adolescence, neurodevelopmental disorders were more frequent (59.3% and 23.5%), including attention deficit disorder, autism, and cognitive disability. In young adults, although the healthy population has been studied more (74.6%), 11.5% of the investigations were carried out in patients with depressive disorders. In the average adult, 22% of the studies were conducted on patients with schizophrenia and 16.9% with multiple sclerosis. In older adults, 26.4% were patients with neurocognitive disorders, such as mild cognitive impairment, Parkinson's, Alzheimer's, o neurocognitive disorders associated with stroke (14.3%).

RQ3 Which EFs showed significative effects after the application of CCTs?

One of the biggest challenges when it came to operationalizing the results of this SR, was to differentiate the executive cognitive processes studied. The term executive functions refer to a theoretical construct associated with cognitive processes of a complex nature, interconnected with other processes and difficult to differentiate, which does not have a unified concept or classification and which, on the contrary, has resulted in multiple explanatory theoretical models.

Fig. 4 shows the frequency of works discriminated by cognitive domain and age group, some of the studies (17.8%) started from models that assume executive function, executive control, or cognitive functioning, as a process unified cognitive function related to the ability to regulate different cognitive, behavioral and affective processes [14, 16]. Another section of the articles (14.4%) took sides with models that assume the concept of "executive functions" in a plural way [17–19], without making an explicit differentiation of each subfunction. Although some studies conceptualize general and nonspecific domains such as cognitive control and self-regulation, these were shown in a much lower proportion (3% & 1.6%).

Most of the articles addressed some EFs in a differentiated and independent way. One of the most approached models was Miyake [17], which differentiates inhibitory control, working memory, and cognitive flexibility as the three central nuclei of EF. Some of the most approached executive functions in research: working memory in 63.3% of the works, inhibitory control in 18.2% and cognitive flexibility in 14.4%. Although they were less frequent (3.5%), some studies showed special interest in the mechanisms of emotional and behavioral regulation, following the EF model of Zelazo [19], who classify EF as cold, or cognitive and hot, or emotional.

Table 5 Clinical population and healthy population by age group

Characteristics of the studied population						
$N = 264$						
Frequency (%)	PC	SC	A	YA	AA	E
Total	5 (1.9)	71 (26.9)	17 (6.4)	35 (13.3)	59 (22.3)	77 (29.2)
Healthy	5 (100)	26 (36.6)	6 (35.3)	26 (74.6)	5 (8.5)	40 (51.9)
Clinical	0	45 (63.4)	11 (64.7)	9 (25.7)	54 (91.58)	37 (48.1)

N Number, *SD* standard deviation, *PC* preschool child, *SC* school child, *A* adolescent, *YA* young adult, *AA* average adult, *E* Elderly

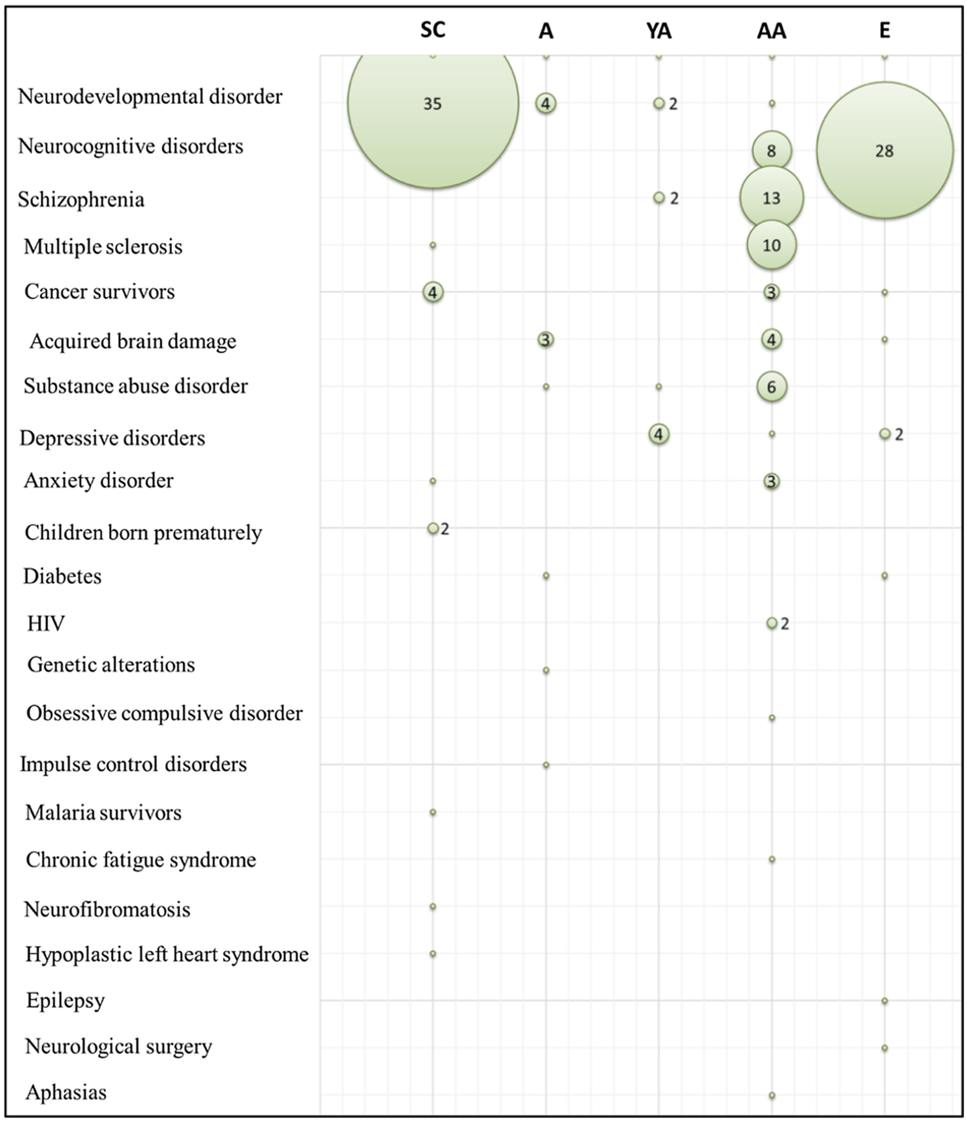

Fig. 3 Clinical condition by age group. *SC* School Child, *A* Adolescent, *YA* Young Adult, *AA* Average Adult, *E* Elderly. Since all the studies in preschool children were conducted in a healthy population, they were not included in this table

Some studies were based on theoretical models that integrate attentional processes within EFs [15, 62, 63], sometimes under the concept of attentional control or executive attention or as one subdomain of attention such as divided, sustained, alternating, selective, among others. 38.3% of the studies addressed attentional processes as an individual component or discriminated by their subdomains.

Other executive functions such as processing speed were included in 18.2% of the investigations; the capacities of planning and cognitive organization in 6.8% of the studies; problem solving in 4.2% and verbal fluency in 3.5%. To a lesser extent, they also presented other cognitive domains usually integrated within the framework of other more general EFs: such as decision making, monitoring of objectives,

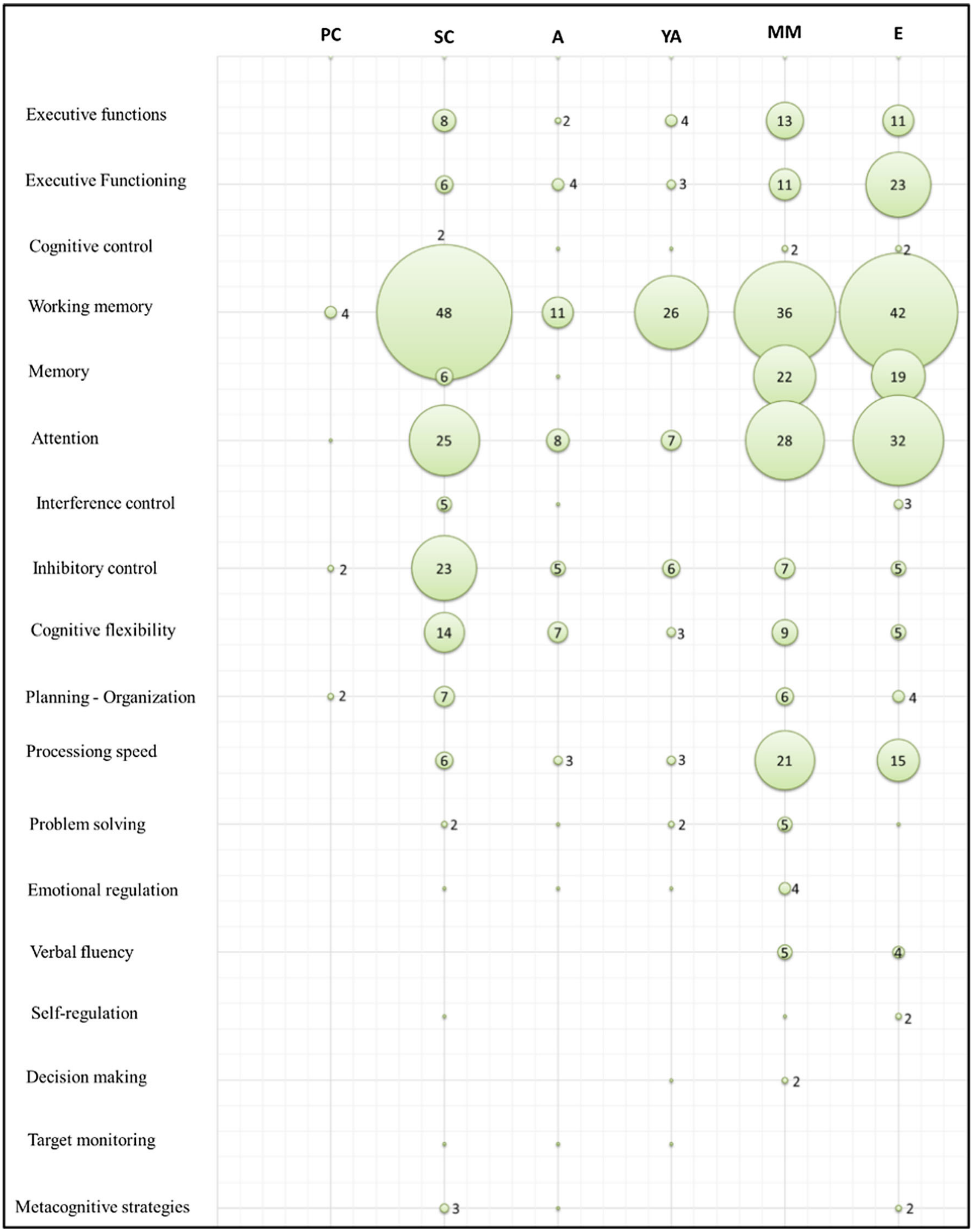

Fig. 4 Executive functions studied by age group. *PC* Preschool Child, *SC* School Child, *A* Adolescent, *YA* Young Adult, *MM* Average Adult, *E* Elderly

and metacognitive strategies. All these were present in 1.2% of the studies. Secondary measures other than executive functions such as memory, such as episodic, procedural, verbal, or spatial memory, were also included in some studies (18.2%).

The comparative of population groups shows trends related to the characteristics of the development of each age group. 80% of the works in preschool children studied working memory (WM), and the remaining 40% studied the inhibitory control and planning skills. In school children,

Table 6 Duration and frequency of intervention programs

	Intervention programs $N = 264$		
	# Weeks	Sessions per week	Total, sessions
Mean (median)	7.9 (6)	3.5 (3)	22.5 (20)
SD (P25–P75)	5.6 (5–10)	2.5 (2–5)	17.9 (12–25)

N Number, *SD* standard deviation, *P25* percentile 25, *P75* percentile 75

this constant was also maintained: WM was the most frequent (67.6%), followed by attention (35.2) and inhibitory control (32.4). In adolescents, WM was also highlighted (64.7%), together with attention (47.1%) and cognitive flexibility (41.2%). WM (74.3) and attention (20%) in young adults. In average adults, WM (61%), attention (47.5), other memory domains (37.3), and processing speed (35.6). In older adults, WM (54.5), attention (41.6), executive functioning (29.9), and other memory domains (24.7).

Although TM was the most studied EF in most populations, other EFs, such as verbal fluency (VF), were exclusively investigated in older adults. This cognitive domain is attributed to a late development that reaches its greatest evolution in adulthood [20], which is why it is understandable that it is not addressed in the early stages. In addition, VF is one of the processes with greater affectation in the cognitive deterioration that appear in advanced ages. In this same sense, processes such as processing speed and decision making were more frequent in young and middle adulthood, processes that are usually altered by neurological damage at these ages, while inhibitory control, cognitive flexibility, and attention, which have accelerated and key development in childhood and adolescence and are usually more affected in neurodevelopmental disorders, were more found in works at these ages.

RQ4 What are the characteristics of the studied CCTs?

The interventions ranged from 1 to 40 weeks, mean of 7.89 weeks. The sessions ranged from 1 to 18 sessions per week, with an average of 3.4 sessions per week and 22.5 sessions (Table 6). The duration of each session ranged from 5 to 180 min; sessions lasted between 20 and 45 min in 48.1% of the studies and between 46 and 60 min in 17.4%. Based on their findings, most researchers suggested that the sessions should not last longer than 45 min.

The evolution of artificial cognitive systems has brought numerous novelties to traditional cognitive stimulation and rehabilitation programs. These innovations include complementary programs from home, remote access to platforms and activities, and venturing into gamified, adaptive programs supported with augmented reality mechanisms, virtual reality [33, 34], or robotics [64]. Some included two or more training programs; therefore, from among the 264 articles reviewed, 279 programs were identified, a figure referring to the total of the programs mentioned in all the investigations, although some were implemented in more than one study. Each paper was coded with a number and listed to facilitate the presentation of the findings; "Appendices B and C" provide a complete list of the details of each study.

More than half (56.2%) of the analyzed programs were composed of gamified activities, some based on the concept of serious games, a term incorporated by Abt [65] to refer to games designed for educational purposes and not for entertainment and that has gained tremendous popularity in recent decades in educational and clinical settings, which has given rise to trends such as "serious games for health." Twelve programs (4.3%) based on augmented reality or virtual reality paradigms were also identified, such as V-Gait, Reh @ City v2.0, Rehabilitation Gaming System (RGS), Systemic Lisbon Battery (SLB), BrightBrainer, Job simulator, NeuroDRIVE, Carnetsoft, Tano and LongGood, SeeMe, V-Gait, Thera Prax, which, in addition to making use of traditional devices (computer, tablet or smartphone), incorporated the use of other devices such as 3D glasses, controllers and simulators, and one of the programs (0.4%), supported by robotics, called Bee-Bot from ER-Lab Trainingrobot. 9.3% of the programs sought to guarantee ecological validity by incorporating activities related to the subject's daily life instead of exercises with arbitrary content. In addition to the intervention, 10% of the implemented programs also had assessment batteries for different cognitive domains.

Regardless of the design and type of activities, 43% of the programs emphasized the adaptive development of the activities so that the level of complexity of the exercises progressively advanced as the subject showed progress in their execution or leveled their level of difficulty to match the participant's baseline skills.

57.7% of the studies evaluated intervention programs supported by recognized commercial, technological resources, some of them available on web platforms, software, or multidevice apps; among them, the most common were: Cogmed (10%), Brain HQ (6,5%), Lumosity (4,7%), Rehacom (3,6%), ThinkRx (1,8%), Mind Frontiers (1,4%), Happyneurompro (1,4%), Captain´s Log (1,4%), Activate (1,4%), SMART (1,1%), and more detail in "Appendix A". Other commercial programs that were part of the studies, although less frequently, were: BrainGymmer, SeeMe, Bee-Bot de ER-Lab Trainingrobot, Better Cognition: Bettercog, Brain Age, BrainQuest, CIRCuiTS, Brainer1, Cognifit, Cogniplus, Cogpack, Comcog, Curb Your Addiction, Neuroracer, Fruit ninja, Job simulator, Jungle Memory, Kroko, Neuronation, NeuroPersonalTrainer, Peak, Plan-It Commander, Posit Science Insight, Power-Afa, PSSCogRehab, Reh @ City v2.0, Rehabilitation Gaming System, RGS, Robot factory, driving simulation with virtual reality, NeuroDRIVE, Star Wars Battlefront, StarCraft 2: Wings of Liberty.

Another proportion of the programs (35.5%) was non-commercial, some designed by university research departments or by a design and programming agency; under the researchers' indications, only 2.5% of the works implemented open access digital resources, 3.6% of institutional clinical programs and only two studies (0.7%) were designed by public entities.

16.5% of the non-commercial programs were based on classic tasks of great recognition and trajectory that implement paradigms to evaluate certain cognitive domains, the most frequent being the n-Back task, among others such as the Go-No go task, the Flanker task, Corsi task, Stroop task, and task change among others. 2.9% were based on previous works programs, 3.6% based on video games (3,6%) such as Alien game, Jungle Memory, Brain game Brian, Watermon, AYCET—All You Can ET, SLB—Systemic Lisbon Battery, Stop & think, Gwakkamole, Magic memory, among others, to which no name was assigned. Less frequently were programs based on instrumental activities of daily living, goal management, web-enabled conversational interactions, TAPAT—Alert Training, ACT—Computerized Auditory Cognitive Training, ECAT, Advanced Contingent Gaze Attention Training, MRCC—Cognitive control multicomponent training, TALI—Attention and learning training initiative, procedural TM training.

Some studies evaluated the efficacy of multimodal programs, in which ACS-based cognitive training was combined with other programs, such as physical training (5.4%), transcranial direct current (1.1%), neurofeedback training (2.2%), meditation and yoga (1.5%), coaching (0.7%) and acupuncture (0.4%).

RQ5 What are the effects on the EF shown by the CCT and their differences by age group?

The results of the randomized clinical trials (RCTs) reviewed found multiple effects in interventions based on digital technologies and artificial cognitive systems; these effects were different depending on the variables evaluated, the purposes of the clinical trial, the type of program implemented, design characteristics, sample sizes, and population characteristics. However, all shed light for future research and the design of interventions that have greater feasibility and seek better effects in the cognitive domains to be trained.

3.1 School Children and Preschoolers

Most studies on preschool and school children determined CCT had moderate to significant effects. In preschool children, a non-commercial program based on the n-back task described effects on working memory and fluid intelligence maintained at 12-month follow-up [27]. Another non-commercial intervention based on the Corsi block task checked for improvements in visual-spatial WM with transfer to task learning [66]. The educational robotics intervention Bee-Bot from ER Lab Trainingrobot improved visuospatial WM and inhibition processes [64]. The Fruit Ninja video game, based on the Go/No go task, improved inhibitory control, transferring to WM and fluid intelligence; electroencephalography (EEG) results indicated an effect on N2; thus, the researchers conclude that response inhibition training appears to potentially improve reasoning ability [67].

The programs investigated in healthy school-age children showed significant improvements in different cognitive domains (Fig. 5), in EF as a general construct [68–70], or in their specific sub-processes such as WM [66, 71–79], inhibition [63, 80–82], interference control [83], attention [71, 84–86], fluid intelligence [75], decision making [85].

A CCT based on classic N-back tasks showed improvements in WM, some with distant transfer to fluid intelligence [75], while others without it [77]. The gamified ThinRx interference control training program demonstrated a distant transfer effect of response inhibition, but it was not maintained at a 3-month follow-up [87]. Cogmed's Robomemo children's version showed better effects on WM when performed in conjunction with training in metacognitive strategy [72]. The non-commercial Nexxo training program, along with self-instructional training (goal setting and planning), was found to help improve EF in children with difficulties in performing inhibition and vigilance tasks [80, 88].

The CCT APRENDO, designed to train WM and attentional control, found that children with lower scores in the pretest showed more significant improvements in the posttest [71]; this is consistent with other studies that affirm that cognitive training has better effects on children with deficits in their cognitive domains than in typically developing children [89]. This finding shows, on the one hand, that cognitive training will not raise the level of EFs above the child's developmental level, however, it will provide learning opportunities and stimulating experiences for children with deficits in their EFs. Some studies found that children with low socioeconomic status (SES) had a reduced performance in the pretest compared to children with medium and high SES, while they were the ones who achieved greater improvements following the intervention [69]. The gamified CCT Match Quest and Recal All game applied in this population had a favorable effect on WM, attention, decision making, and motor control [85]. Some studies have shown that low-income children with low academic performance could benefit from specific training programs based on classical tasks [69].

Studies that evaluated the impact of EFs training on children's academic performance [82] found that directed EF training can have beneficial effects on low-performing children [69], with significant improvement in cognitive skills, such as non-verbal IQ, inhibition, reading [81, 90–92], and mathematical reasoning [70, 72, 73, 78, 79, 90, 91]. This

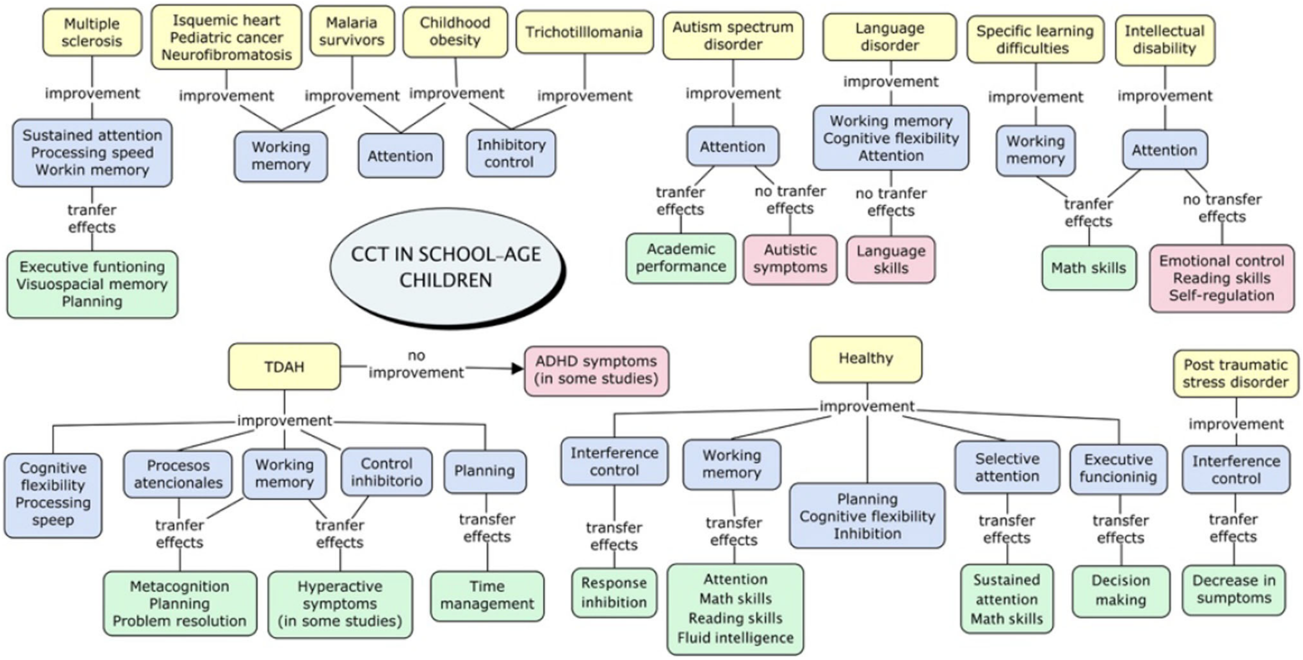

Fig. 5 Conceptual model of the effects of CCT on school-age children

finding is in line with previous studies showing that working memory capacity is closely related to mathematical thinking and, in particular, to speed in solving arithmetic problems [79]. Some RCTs with Cogmed and immediate transfer to WM showed distant transfer to performance in reading and mathematics [74, 92] and academic performance [70, 72]. However, some of these effects were sustained for more than one year [92], while others were not [74].

Regarding children with clinical conditions (see Fig. 6), an RCT with Cogmed in pediatric cancer survivors showed improvements in their WM with close transfer in other verbal and spatial WM measures, which was maintained for six months. The cognitive processes of children with this condition tend to worsen, so this CCT is postulated as an intervention that slows down the deterioration and stimulates their cognitive development [93]. Researchers have concluded that TM computerized cognitive training is feasible, acceptable, effective, and is associated with neuroplasticity among survivors of childhood cancer, showing adherence to training and satisfaction in participants [94]; they suggest future studies should evaluate brain changes identified in neuroimaging as indicative of training-related neuroplasticity [95].

In children with pediatric multiple sclerosis, a noncommercial CCT based on attention training improved concentration, attention, processing speed, TM, and cognitive flexibility, with distant transfer to executive functioning, updating, and planning strategies visuospatial memory [96]. In children with post-traumatic stress disorder, the noncommercial reading span program decreased the recurrence of symptoms and the performance of interference control [97]. In children with trichotillomania, a CCT based on the classic Go/No go task proved to be a potentially helpful intervention to improve inhibitory control [98]. Cogmed revealed effects on neuronal measures and cognitive performance of WM in children with neurofibromatosis [99] and hypoplastic left heart syndrome [100]. For malaria survivors, Captain's Log improved attention and memory outcomes [84].

Concerning children with neurodevelopmental disorders (Fig. 5), for children with intellectual and developmental disabilities, the TALI attention training program validated distant transfer to mathematics and arithmetic, however, not to reading, executive functions, and emotional control [101]. In children with specific learning difficulties, the analysis of event-related potentials showed that the amplitudes N160 (visual recognition) and P300 (update, working memory) were markedly lower in the control groups than in those who participated in a refresher training, with a transfer effect to mathematical performance [73]. In children with autism spectrum disorders (ASD), the Progressive Cognitive Attention Training, based on a continuous performance task, described improvements in academic performance but did not reduce autistic symptomatology [102]. An RCT with Cogmed RM, although it did not evaluate its effect, found it feasible and beneficial to implement it in the home with an autistic population [103]; as long as families are trained in the use of behavior management techniques, it can facilitate adherence to training. In children with language disorders, the CCT Magic Memory based on classical tasks improved

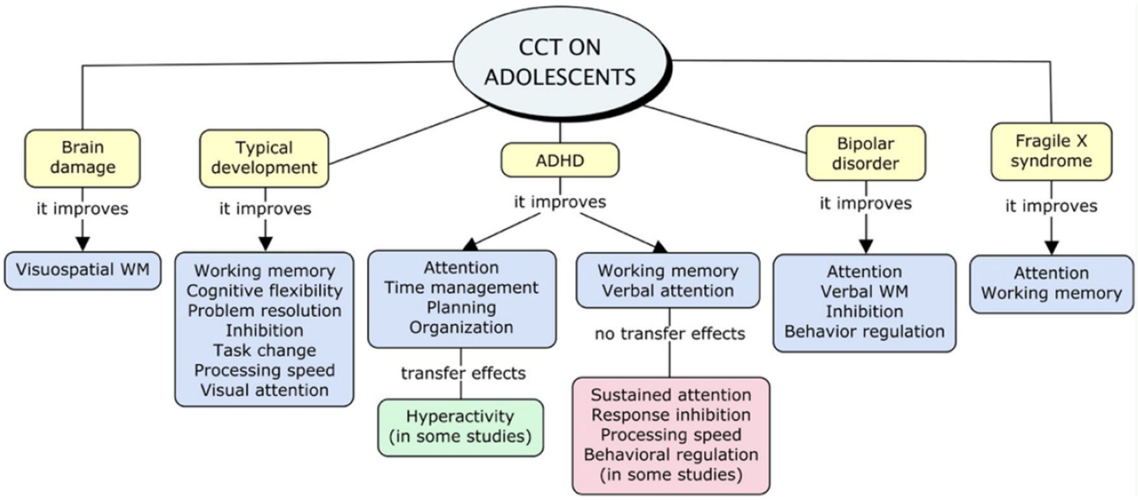

Fig. 6 Conceptual model of the effects of CCT on adolescents

WM, attention, and processing speed without transfer to language skills [89].

The most studied clinical condition in the reviewed papers was ADHD. Non-commercial video game-based programs showed positive effects in different cognitive domains in this population: BrainGame Brian was shown to improve WM and IQ; although improvements in untrained EFs and behavior were nonspecific [104], one RCT found that improvement in WM, this program decreased the symptoms of hyperactivity [105], while another RCT found small effect sizes that lost significance when correcting them [29]. The CCT Stop & Think produced immediate transfer effects in IQ and far in performance in mathematics and science [82]. Neuroracer demonstrated improvements in attentional functioning and spatial working memory for the moderate ADHD group and a high severity subgroup, but not for the non-ADHD group [106]. The AKL-T01 program significantly improved attention performance [107].

The commercial gamified ThinkRx CCT was useful in cognitive remediation programs for children and adolescents with attention problems, with cognitive and behavioral benefits [108]. ThinkRx also allowed to identify significant improvements in associative memory, long-term memory, WM, visual and auditory processing, and processing speed in children with ADHD, and the researchers proposed the design of activities that involve multiple cognitive abilities. [109, 110]. Two RCTs evaluated the CCT of serious games with Plan-It Commander. The first described that girls, in general, and boys with less hyperactivity, had higher achievements in planning and organization [111]. The second showed improvements in time management, social skills, and WM. Serious games showed the potential to improve performance in daily life skills in children with ADHD [112].

A multimodal CCT with Cogniplus and Neurofeedback training showed favorable changes in ADHD symptoms and EF [38]. The progressive attention training program exhibited improvements in spatial-selective attention and executive attention, with gains maintained over time, and a modest transfer to sustained attention, although this did not imply improvement in ADHD symptoms [113].

An RCT that evaluated the use of CCT in conjunction with ADHD medication demonstrated significantly improved performance in attention, WM, cognitive control in both children with and without medication and better academic outcomes [86]. A functional magnetic resonance imaging study on the neural effects of a combined program with medication and the CCT ACTIVATE described improvements in WM, IQ, sustained attention, and changes in brain function related to performance on trained tasks [114].

Some CCTs did not demonstrate the expected effects. In the population of children born prematurely, WM training with Cogmed did not confer significant improvements in any EF [115]. BrainGame Brian was also ineffective in improving attention and academic performance in this population [116]. ACTIVATE in children with ADHD also found no significant effects on attention, inhibition, flexibility, or cognitive control [117]. Some CCTs based on basic tasks oriented to attention and inhibitory control in children with obesity did not demonstrate significant effects on these cognitive domains in any way that would impact the maintenance of weight loss [118]. A non-commercial visual attention program in children with autism did not show transference beyond the trained task [119].

3.2 Adolescents

Cogmed was the most studied program in adolescents: in an RCT, in some investigations, it was demonstrated to improve WM and generate transfer in different cognitive domains in young people with pediatric bipolar disorder and ADHD, bipolar youth improved basic attention and verbal working memory, inhibition and the regulation of behavior; young people with ADHD improved visuospatial WM and verbal attention, but showed transfer to behavioral regulation (93). In youth with Fragile X syndrome, Cogmed improved attention, working memory, and executive functioning [120]. In adolescents with ADHD, Cogmed demonstrated specific WM gains without transfer to sustained attention, response inhibition, or processing speed. However, MRI in these youths showed greater activation in WM-linked frontoparietal brain regions [121].

The video games Alien Game [122] and All you can ET [123] improved the change of tasks in healthy adolescents. Lumosity improved visual-spatial WM in adolescents with congenital or acquired brain damage [124, 125]. The Tree of intelligences videogame improved attention, time management, planning, and organization in adolescents with ADHD and a reduction in symptoms of hyperactivity [126]. A non-commercial CCT, based on brain plasticity theory, improves different components of working memory in adolescents with ADHD. They managed to obtain a level of performance similar to that of adolescents in typical development [127]. An RCT performed with Brain HQ described significant gains in processing speed, visual attention, visual cognitive control, and global cognition, and moderate gains in WM, cognitive flexibility, problem solving, and inhibition [128] (Fig. 6).

3.3 Young Adult

Most of the investigations on young adults were carried out in healthy people (Fig. 7). Training in the classic N-back task, used to train WM, was one of the most frequent approaches in this population. In some studies, it generated improvements in WM updating, limited to very similar tasks to those trained [129], while in others, when implemented with strategy training, it showed transfer to other domains [130]. Another study with n-back demonstrated transfer to the ability to inhibit irrelevant information [131]. In another work, the n-back task showed a modest effect in double task distant transfer [132]. The n-back task with Brain Twister2 generated more complex training demands, which became a more significant transfer in a structurally different WM task, with distant transfer to attentional control [133]. The use of n-back in conjunction with neurofeedback training showed improvements in executive function after a relatively short training period [134].

The CCT Mind Frontiers showed immediate transfer of n-back to other WM tasks and far transfer in lower-level skills such as perception speed and reaction times, which improved the processing of more complex tasks [135]. An RCT compared Mind Frontiers' unimodal treatment with a multimodal treatment that included meditation and high-intensity cardio-resistance training, both programs generated significant improvements in decision making, with better effects on EF with the multimodal program [136].

Some studies did not show the expected effects or limited distant transfer. A CCT based on the Stroop task showed improvement in WM without a reliable transfer effect on conflict resolution [137]. While the Stroop task for Inhibitory Control training was not transferred to an untrained inhibition task, neither did it transfer to WM, flexibility, or planning [138]. Lumosity achieved improvements in measures of flexibility, attention, and reaction times, but these changes were not reflected in the evoked potentials since the P3 component, related to attention, did not show the expected differences after training [139]. Other studies did not show the expected effects; in one RCT, Cogmed only improved specific WM tasks, making the degree of generalizability very limited [83].

Other CCT demonstrated improvements in WM in healthy adults, end effects distant transfer to visual attention [140] or other cognitive domains [141]. The Gwakkamol gamified CCT, designed to train Inhibition, did not identify any significant effect caused by the lack of a challenge at the level required by the participants [142], nor did MultiTask have a significant effect on WM, switching, or Inhibition, although for the participants it might because the measures used were not representative [143]. A non-commercial attentional control CCT improved selective attention, WM, and decision making [144]. In this vein, some researchers in their clinical trials conclude that the effect of distant transfer after EF training is far from clear [145].In young adults with schizophrenia, training with Brain HQ affected processing speed, WM, and attention [146], with more significant changes and better effects in patients with low or impaired initial performance, than in patients with high performance [147]. In patients with mood disorders, the intervention with Cogtrain improved executive functioning and processing speed, with a decrease in cognitive depressive symptoms, but without improvements in the mood [148]. In contrast, WM training with Cogmed improved attention, self-regulation, and stress dysregulation symptoms [149].

3.4 Average Adult

91.5% of the studies carried out on an average adult were in the clinical population (Fig. 8). A study in young adults, based on the Flanker task, showed on MRI that the amygdala-IFG connectivity was significantly increased after executive control training. These findings are the first to show that non-emotional training can alter amygdala-prefrontal connectivity, as well as improvements in attention, emotional

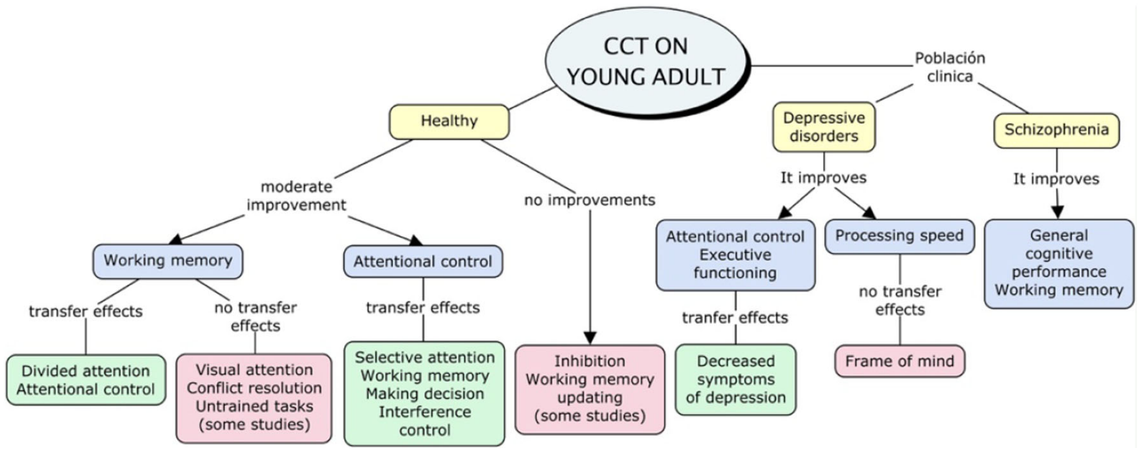

Fig. 7 Conceptual model of the effects of CCT on young adults

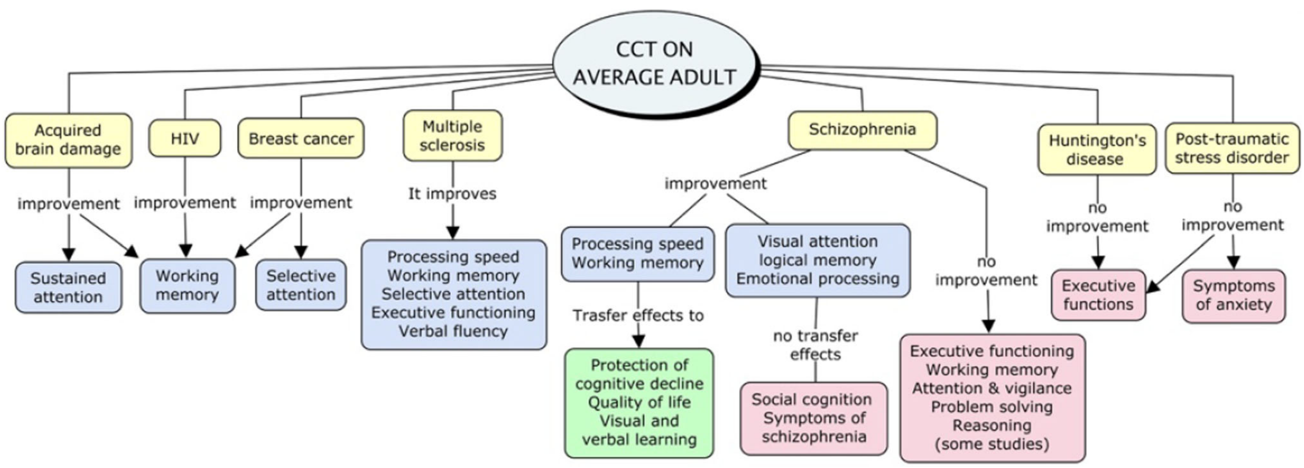

Fig. 8 Conceptual model of the effects of CCT on Average adult

control, and inhibitory control when performed with a constant frequency [150].

Five RCTs have been identified in adults with multiple sclerosis. One of these compared Captain's log Mindpower builder with manual and combined training, each program showing effects on WM, executive functioning, and processing speed [151]. Cogni-Track improved WM in this population; the researchers pointed out that its adaptive workload was a crucial characteristic of intervention effectiveness since it allowed for adaptation to the participant's particular needs [152]. N-back training showed favorable effects on this population's verbal memory, working memory, processing speed, and phonetic fluency [153]. Rehacom showed significant improvements in verbal and visuospatial episodic memory, processing speed, attention, and executive functioning, which was maintained for six months [154]; in an MRI study, this same program showed significant alterations in the brain during the task n-back, although this was not maintained after the end of the treatment [155]. Other studies with gamified CCT showed notable improvements in processing speed in adults with multiple sclerosis [156].

Some RCTs with Brain HQ showed remarkable effects in adults with schizophrenia. One of these found improvements in TM [157], while another showed the viability of Brain HQ in combination with pharmacological treatment [158]; some showed viability and adherence to remote administration of the intervention, with improvements in global cognition, verbal memory, problem solving [159], as well as attention, processing speed, working memory, and problem solving. However, another RCT showed that, despite adherence, they found no significant effects on executive functioning, WM, attention, or problem solving with Brain HQ in adults with schizophrenia [160].

Neuronpersonaltrainer, a CCT designed specifically for patients with schizophrenia, was shown to favor visual attention, logical memory, and emotional processing in patients in the early stages of schizophrenia without transfer to the functioning of daily life and social cognition [161, 162]. Another program designed for this population was CIRCuiTS, which demonstrated that it could protect against cognitive impairment [163] and promote improvements in processing speed, WM, and visual and verbal learning, although it did not affect vigilance reasoning and attention, and problem solving [164]. The intervention with the Cognitive Remediation Rehabilitation Software Jcores in schizophrenic patients showed microstructural changes in the posterior lobe of the left cerebellum associated with changes in verbal fluency [165]. However, some RCTs with Brain HQ [166] and Cogpack [153] found no significant effects on the interventions in this population.

In people with anxiety disorder, adaptive n-back training led to improvements in WM, with transfer to a reduction of self-reported worry and anxiety symptoms [167]. In depressed patients with cognitive deficits, Cogniplus led to a significant improvement in attention performance, with transfer to daily living skills and psychosocial functioning [168]. While the CCT PEAK, although it showed gains in executive functioning and processing speed in patients with depression, it did not improve mood or daily functioning [169]. In post-traumatic stress, cognitive-affective training with a gamified CCT did not show generalized benefit on EFs or symptoms [170]. In patients with obsessive–compulsive disorder, cognitive control training with Cogtrain was shown to strengthen the ability to defocus irrelevant information (including obsessions), with improvements in focus on the task and daily functioning [148].

In adults with acquired brain damage, an RCT compared a pencil and paper intervention with the CCT Rehacom, finding superiority in the latter's effects, which was shown to improve memory and sustained attention, and demonstrated superiority with the program [171]. However, with the same population, the CCT Cognifit did not show the effects of training in any cognitive process [172]. In adults with cognitive impairment, HappyneuronPro generated improvements in executive functioning and increased the power of the frontal theta frequency, reducing the power of the posterior alpha frequency in the EEG after two weeks of training [173]. In patients with stroke, CCT like BrainGymmer, showed effects on cognitive flexibility [174] and the Erica cognitive remediation platform, on attention and memory capacity, with benefits on mood [175]. Although BrainGymmer demonstrated improvements in some EFs, these occurred in both the intervention group and the control groups, suggesting that the improvement was due to the nonspecific effects of training [176].

Cogmed was shown to improve WM verbal function in drug abuse-related disorders, but did not show transfer effects or reduce drug abuse symptoms [177, 178]. Although CCT Curb your addiction only evaluated its effects with self-reported measures, it showed that WM training, in addition to traditional treatment, can reduce the clinical symptoms of impulsivity and improve self-regulation in methamphetamine users [179], as well as a CCT of goal management together with pharmacological treatment, showed a significant effect on inhibitory control and the general execution scheme that allows to achieve the objectives, with transfer to working memory and impulsivity and planning [180], training with Lumosity improved performance in an inhibition task and quality of life in this population [181]. A non-commercial CCT did not significantly affect EF in adult smokers [182].

In women with breast cancer, HappyneuronPro improved memory and concentration, verbal learning, and WM, which were maintained after five months [183]. This same program in patients with Huntington's disease neither effect nor adherence to it [184]. In HIV patients, CCT Lumosity [185] and PSSCogRehab [186] successfully reduced WM deficits.

3.5 Older Adults

In healthy older adults, the studies explored various EF training programs based on digital technologies and artificial cognitive systems (Fig. 9). The gamified Brain Age program affected interference control and mathematical reasoning [187], while the Star Wars Battlefront video game improved visual attention, task switching, and WM domains, which were not sustained after one month [188]. Training with lumosity improved visuospatial WM, episodic memory, and short-term memory in this population [189], and BrainGymmer produced improvements in cognitive flexibility, with near and far transfer to other domains [190]. The HappyneuronPro neurorehabilitation platform effectively strengthened visuospatial skills and some EFs such as visual processing speed, divided attention, and selective attention [191].

The n-back training showed improvements in WM in general [192, 193] and visuospatial and verbal WM in particular [26]. Other classical task-based programs showed effects on task change but with very limited close transfer [194]. Some free access CCT, such as Fresh minder, Mental-akiv, and Mentaga, improved WM [195]. Rehacom's WOME module significantly improved WM with stable effects and relevant impact on daily life [196]. Itrain, a training in simultaneous management of verbal operations, improved EF with close transfer to untrained verbal WM tasks and far transfer to language fluency, sentence memory, and resolution of syntactic ambiguity, implying that training WM can be a critical resource in language performance in older adulthood [197]. Verbal fluency in patients with dementia showed improvements in a non-commercial CCT, with benefits in psychological well-being [198]. A multicomponent cognitive control training showed benefits in this cognitive domain, with transfer to recognition memory and general cognitive functioning; magnetic resonance imaging also showed that the frontoparietal cognitive control network seemed to expand after training [199].

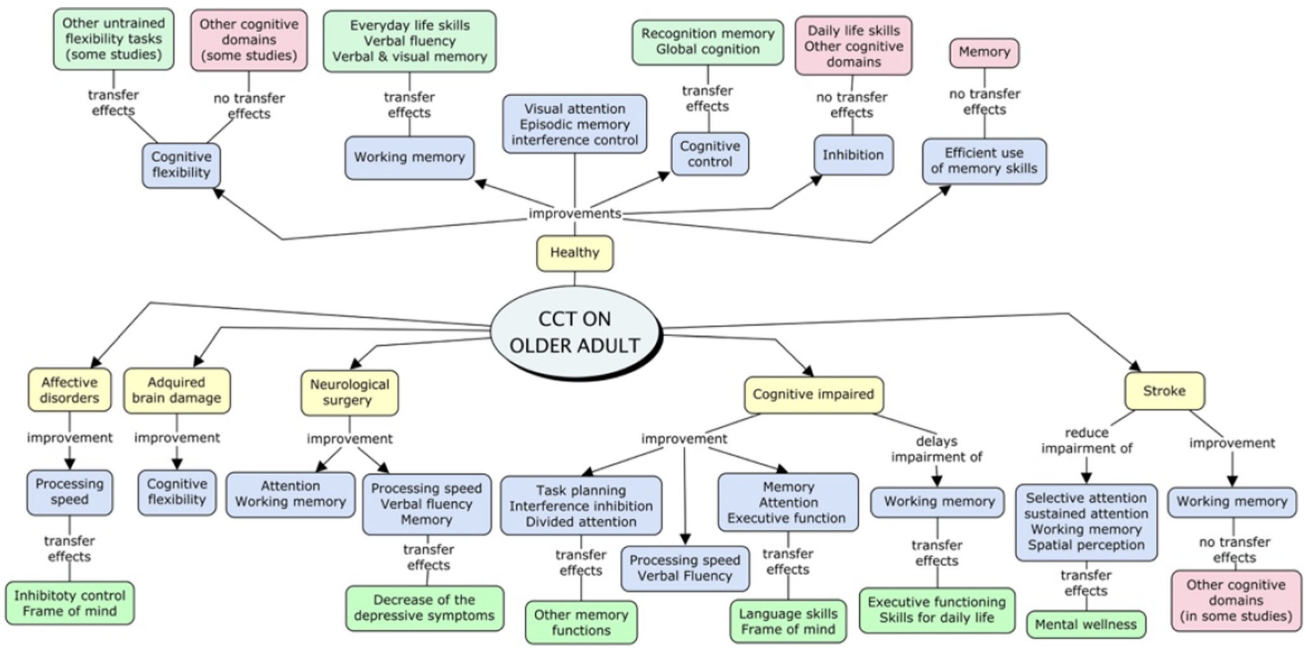

Fig. 9 Conceptual model of the effects of CCT on older adults

Some CCTs integrated the virtual reality paradigm in healthy older adults, such as the VR-CS program, which showed favorable effects on general cognition and executive functions, particularly attention [200]. These programs were also shown to be promising in patients with mild cognitive impairment, such as Job Stimulator combined with a physical activity program, which showed significant improvements in executive function, single-task, and dual-motor gait performance [201]. NeuroDRIVE showed a generally positive effect on cognitive flexibility in patients with acquired brain damage [202]. In patients with mild cognitive impairment and dementia, virtual reality-based training showed greater adherence and satisfaction than the pencil and paper versions [203].

In healthy older adults, multimodal programs combining CCT with physical exercise were also studied. Through electroencephalogram, effects of SMATH strategic memory advanced reasoning training and aerobic exercise, on neural activity related to processing speed in the prefrontal cortex, while aerobic exercise alone did not show benefits of neuronal activity [204]. On the other hand, the SDAEWMT method, a dual-task training performed simultaneously that includes aerobic exercise training and WM training with Brain Age video game, demonstrated an effect on executive function without broader transfer effects [205]. A non-commercial CCT combined with aerobic exercise in sequential or simultaneous formats showed significant gains in executive function and WM with close transfer to similar activities [206]. EXCOG was another program that linked aerobic and cognitive challenges; it showed better results than the other treatments alone [207]. In patients with heart failure, a combined program of aerobic exercise and cognitive training with Brain HQ generated a significant improvement in verbal memory that was sustained at 3 and 6 months compared to exercise alone [208]. In older adults with hearing loss, a CCT combined with aerobic exercise found gains in auditory TM, more noticeable in sequential training than simultaneous training [209].

Some CCTs were shown to improve performance in domains associated with the trained tasks, without showing significant near or far transfer [194, 210–212], nor did they lead to structural brain changes evidenced by magnetic resonance imaging [213–215]. Results suggest that not all training procedures produce benefits in terms of generalization. Here there is evidence of a lack of transfer to daily life.

Concerning older adults with clinical conditions (Fig. 10), patients with neurological surgery had improvements in attention and WM after training with Cogmed, with transfer to processing speed, verbal learning and memory, improvements in quality of life, and symptoms of depression and anxiety [216]. In patients with stroke, the Rehabilitation Gaming System (RGS), reduces the deterioration in selective attention and working memory and a positive change in the mental well-being of the patients [217]. In older adults with depression, a processing speed training game showed improvement in this cognitive domain, with transfer to inhibition performance and mood [218].

In patients with ischemic cerebrovascular accident, PSS-CogRehab, a CCT with a virtual environment, significantly improved spatial perception, memory, concentration, and

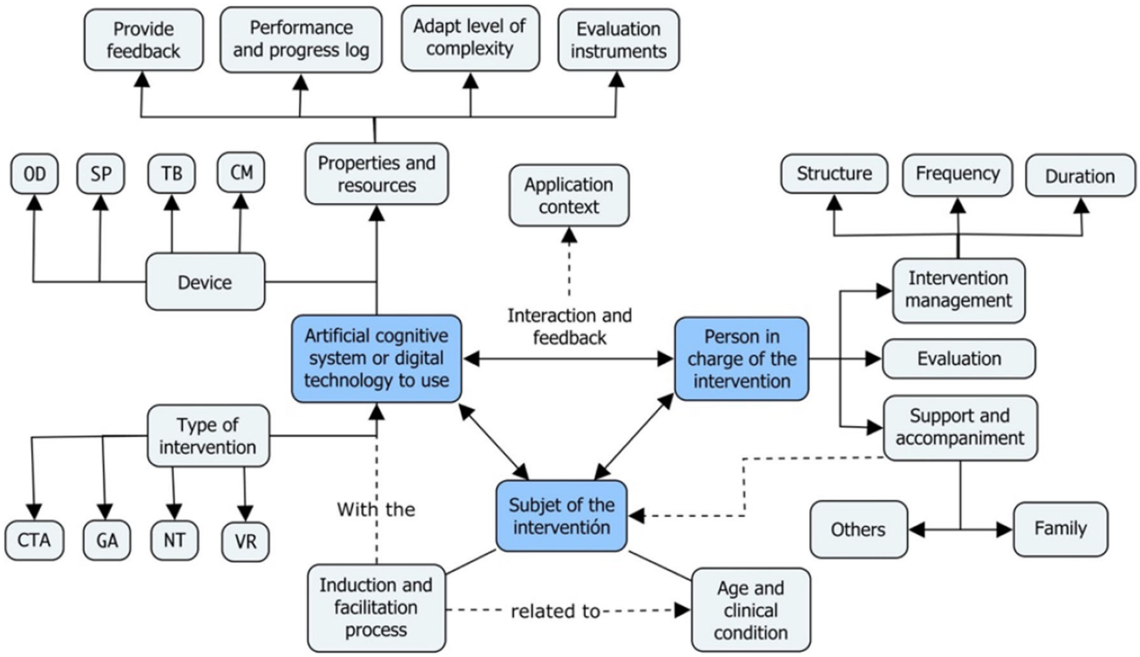

Fig. 10 Intervention model. *OD* others device, *SP* smartphone, *TB* Tablet, *CM* computer, *CTA* classic task-based activities, *NT* Neurofeedback, *VR* Virtual reality

problem solving [219]; in the same population, Lumosity was shown to improve goal achievement functional and the use of the internal strategy, increase yields in WM, although without significant transfer effects [220]. A combined program with Rehacom and acupuncture showed better effects on executive functions, attention, planning, short-term memory, and spatial and temporal orientation processes than with cognitive training alone [221, 222]. The computerized complex of neuropsychological correction KtasSmu showed that both the training group and the entertainment games group activated the patients' attention, accelerated their reaction time, improved their visuospatial orientation and their memory, which seems to show that any nonspecific cognitive stimulation is effective for cognitive correction in early recovery from a stroke [223].

In patients with mild cognitive impairment, non-commercial training based on video games has been shown to delay the decrease in WM, with transfer effect to other untrained executive functions and the vital capacity of life [224]. In this population, comparative studies have shown that Bettercog may be a better therapeutic tool than Comcog [225]. In Alzheimer's patients, a non-commercial neuroplasticity-based program showed constant improvements in processing speed [226], while Brainer1 was shown to support improvement in memory, attention, executive function, and language skills, which was sustained by six months. However, it suggests tasks with greater ecological validity [227]. In this population, the CCT CORE achieved improvements in task planning, interference inhibition, and divided attention, which, although it showed transfer to other memory functions, this benefit did not seem to be sustained over time. Therefore, the authors conclude that the improvement in memory does not reflect a specific improvement in this domain but rather a more efficient and strategic use of memory skills that have been learned during training [228]. In conjunction with active transcranial direct current stimulation, Brain HQ proved to be a helpful approach to managing cognitive dysfunctions of attentional and executive functions and mood in older adults with Parkinson's [40].

4 Discussion

The systematic review shows a snapshot of the potential use of digital technologies and artificial cognitive systems in rehabilitation and cognitive stimulation programs in different population groups. Table 7 presents a synthesis of characteristics of the interventions according to age groups. It can be observed that regardless of the subject's age, the programs with game-based and classic tasks-based activities continue to have great acceptance. In contrast, programs based on virtual reality and those that prioritize the ecological validity of their activities were studied mainly in older adults. The incursion of neurofeedback training has begun to gain notoriety in recent years among school age to older adulthood subjects, while other initiatives such as robotics are very briefly represented among the reviewed studies.

Table 7 Summary of the characteristics of the interventions by age group

	Population characteristics	Executive functions	Other processes	Program features	Most common programs
PC	Healthy	WM, IC	Fluid Intelligence	Classic tasks, video games, robotics	Bee bot, Fruit ninja
SC	Healthy Neurodevelopment disorders Cancer survivor	EF, WM, IC, CF, AP	Academic performance, impulsive symptoms, time management, fluid Intelligence, hyperactive symptoms	Classic tasks, video games, gamified activities, neurofeedback training, interactions combined with physical activity	Cogmed, Neuroracer, Nexxo training, AKL-T01, Activate, Match-Quest, Aprendo, Cogniplus, Cogniplus, Braingame Brian, Stop & Think, ThinkRx, Plan-It Commander, ACTIVATE, ThinRx,
A	Healthy Neurodevelopment disorders Acquired brain damage	EF, WM, IC, CF, AP	Time management, problem solving, hyperactive symptoms	Gamified activities, video games	Cogmed, Alient game, All you can ET Lumosity, BrainHQ
YA	Healthy Depressive disorders	WM, AP, IC	Mood, anxiety symptoms, decision making	Classic tasks, Gamified activities, neurofeedback training	Brain Twister2, Mind Frontiers, Lumosity Cogmed, Cogtrain, Gwakkamol, MultiTask
AA	Multiple sclerosis Schizophrenia Substance abuse disorders	EF,WM, AP, PS	Memory, anxiety, functioning in daily life, protection from cognitive impairment, Self-regulation	Classic tasks, Gamified activities, combined with medication	Rehacom, Brain HQ, Circuits, Cogtrain, Cognifit, Captain's log, Peak, Cogpack, Rehacom, Jcores VCAT-J, PSSCogRehab
E	Neurocognitive disorders Healthy Stroke	VF,WM, AP, PS	Quality of life, driving skills, psychological well-being, functioning in daily life	Classic tasks, virtual reality, activities with ecological validity, gamified activities, combined with physical activity, neurofeedback	BrainGymer, Smath, Neurodriver, Brain age, Rehacom, Job Stimulator, Lumosity, Happyneuron

WM Working memory, *AP* Attentional processes, *CF* Cognitive flexibility, *IC* Inhibitory control, *PS* Processing speed, *VF* Verbal fluidity, *PC* Preschool child, *SC* School child, *A* adolescent, *YA* Young adult, *AA* Average adult, *E* Elderly

The executive function varied according to the population group, closely related to the characteristics of the population, since at school age, the most studied clinical condition was ADHD and ASD, and the executive functions to intervene were those related to those disorders, such as working memory, attention, and inhibitory control. At the same time, in older adults, the interventions were directed to both neurocognitive disorders such as Alzheimer's or to prevent cognitive decline in a healthy population, in that sense, the interventions were also interested in other attentional processes, processing speed, and verbal fluency.

Among the recognized advantages of this new cognitive training paradigm, there is the assurance of a more systematic, adaptive intervention scheme with permanent feedback, more superb usability, and better accessibility, as well as its applicability to the training of a vast repertoire of cognitive domains, ranging from improving motor function, basic cognitive processes such as perception, sensory discrimination and reaction times, to more complex processes such as language, IQ and executive functions. Interest in this software paradigm is on the rise, driving the emergence of commercial platforms, software and applications, and non-commercial initiatives worldwide. This impulse has been joined by clinical institutions, university research centers, and private organizations. Although the most significant interest has been its application in clinical settings, important initiatives can also be recognized for their approach in educational settings, especially in developing children. However, this remains an area that requires further exploration and rigorous studies to support the efficacy and effect of these interventions (Fig. 10).

The studies reviewed throughout highlight the benefits of cognitive training programs based on artificial cognitive systems. The possibility of remote access, offered by digital technologies, allows for the decentralization of the intervention and takes it from the laboratory or clinical institutions to the home, school, and workplace. Moreover, the multiplatform and multidevice nature (computers, tablets, and smartphones) of some ACS increases usability and restricts logistics, infrastructure, or equipment limitations. This dynamic enables the subject to interact with greater autonomy [68], so that direct and constant feedback is provided by an ACS agent. This in turn gives the health and education professionals greater flexibility to attend various subjects over time [129], without neglecting companionship, instructional support and follow-up of the intervention process. The possibility of remote access positively affected retention rates, adherence to treatment, and even more notable cognitive and functional improvements than some laboratory treatments [159]. Another virtue of CCT is to allow for an experience of sensory integration so that several sensory modalities are involved in the development of activities, which has been shown to favor learning and neurological stimulation [70].

Some CTTs were hosted on online platforms, which provide the professional in charge of the intervention with a vast repository of activities, which translates into diversification of tasks and the possibility of managing the sessions of the programs; on the other hand, it allows content managers to update and create new exercises constantly. These platforms also allow for the constant recording of the performance and evolution of the subject, evaluation, monitoring, providing real-time feedback to participants and professionals, and the generation of reports and statistics. Some of these platforms also have digitized neuropsychological tests and automatic scales calculation.

Regardless of the design and type of activities in CCTs, 43% emphasized the advantages of activities with adaptive complexity, that is, the complexity level of exercises advances progressively according to improvements of the subject and adjusts their level of difficulty to suit the baseline skills of the participant [222]. The researchers found that an adaptive workload that adapts to the subject's needs, is crucial to the effectiveness of an intervention. Moreover, it enables transfer to untrained cognitive domains with a positive long-term effect [152]. This adaptability responds to the execution of computer logarithms that act automatically from the received information, in this case, the participant's performance, which is possible thanks to the machine learning capabilities of the agent of the implemented artificial cognitive system. Therefore, this adaptive nature was seen by researchers as a key contribution of cognitive training based on artificial cognitive systems.

56.2% of the analyzed programs were composed of activities based on games, even commercial video games, but implemented for cognitive training, like serious health games, intentionally designed to train some cognitive domain or activities adapted to game modes, like traditional pencil and paper activities or classic gamified tasks. The researchers found that a serious game scheme fosters an intrinsically motivating environment [68, 170], this being a determining factor for the success of the intervention. Motivation, adherence, and cognitive improvement with gamified programs were observed in different population groups, finding that even at advanced ages, a certain degree of plasticity is preserved, and training with video games could be an effective intervention tool [189]. Additionally, it was found that this type of program could be easily incorporated into real-life school environments, with positive consequences for academic success, not only for children with typical development but also for children with special educational needs [90]. Video games and serious games require the subject to generate strategies of variable complexity and emotional regulatory challenges, with benefits in executive functioning, especially when they offer a challenging environment with increasing complexity.

Another trend that has gained interest in the academic community is the incorporation of virtual reality mechanisms, and they have been predominantly studied in the elderly population. They showed greater adherence and satisfaction than the pencil and paper versions of the activities [203]. The virtual reality programs had the purpose of allowing for a more immersive, complete experience, simulating everyday life environments, which at the same time provides alternatives to guarantee the ecological validity of the programs [33, 34].

Studies found that cognitive training programs based on digital technologies and artificial cognitive systems allow to overcome some of the limitations of traditional pencil and paper interventions, provide the opportunity to reach more people, and diversify their use and intervention objectives, demonstrating superiority in several aspects [162, 200]. However, they emphasize the need to consider differences in age, educational level, level of cognitive functioning, and participants' familiarity with ACS [200]. For this reason, to guarantee efficacy, adherence, and permanence in treatment, the researchers suggest encouraging the use of the computer or mobile devices and facilitating the use of the technologies to be implemented [229].

Based on all the emerging findings of this systematic review, a model has been formulated that integrates the elements involved in an intervention program based on artificial cognitive systems or digital technology. As shown in Fig. 10, at the center of any intervention program of this nature, there is the triple relationship that interweaves between the subject receiving the intervention, the subject in charge of the intervention, and the artificial cognitive system with which both they will interact. This relationship is bidirectional, generates constant and dynamic feedback between these three central axes, and is influenced by the context of the application of the intervention program.

The type of intervention, the device to be used, and its properties (such as providing constant feedback to the participant, recording and storing their progress, issuing reports, and providing inputs for the evaluation) should be established depending on the selected ACS. The person in charge of the intervention, for their part, is in charge of managing the program, defining the frequency, structure, and duration of the sessions, evaluating the impact of these, and providing advice and constant support to the subject of the intervention, the family and the other people involved, such as caregivers, assistants, teachers, and other professionals. As was already mentioned, it is crucial to promote an induction and familiarization scheme with the artificial cognitive system with which they will interact throughout the intervention. Said induction must respond to the person's needs, age, previous experience, level of training, and clinical condition.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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