Rehabilitation of Executive Functions: Systematic Review of Technological Stimulation Devices

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Abstract. Executive functions are high-level mental abilities that are located in the frontal lobe and allow humans to regulate their behavior. These cognitive skills are initiative, working memory, problem solving ability, inhibition, monitoring, verification, planning, among others. In the processes of stimulation or rehabilitation of executive functions, we work with material based on pencil and paper, therefore, it is essential to generate technological proposals that can help in the processes of rehabilitation of executive functions. In this context, we present a research that conducted a quantitative systematic review of technological devices used for neuropsychological stimulation and rehabilitation of executive functions. The research concludes by analyzing the contribution of having technological resources to rehabilitate executive functions and the need for future research to develop new technological tools in the neuropsychological rehabilitation process.

Keywords: Neuropsychological Rehabilitation · Technological Devices · Executive Functions · Systematic review

1 Introduction

The conscious activity of the human being is product of the work of several brain structures, being the frontal lobe one of the most important parts for human beings to regulate our impulses, behavior, desires and everything we are able to produce [1, 2].

Several researches have described that human beings who have an adequate development of the central nervous system can act with awareness of the consequences of their actions, while people who have some kind of frontal damage (Fig. 1), act irresponsibly, without having objectives or a clear planning of what they want to achieve in life [3, 4].

The mental functions that allow this conscious work in the human being are the executive functions [5, 6]. These cognitive abilities are defined as high-level mental skills that allow human beings to have a creative and effective behavior within the respect of social parameters [7].

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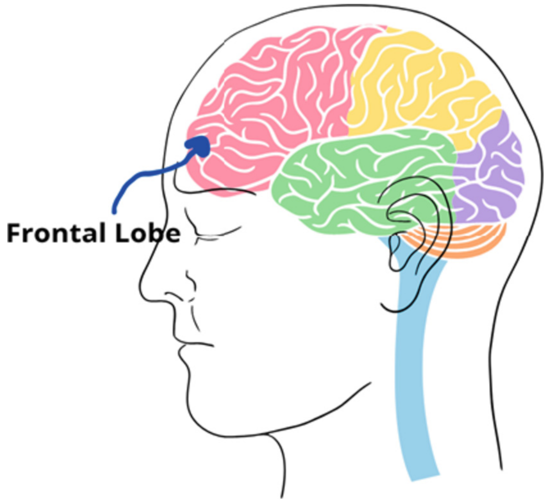

Fig. 1. Graphic location of the frontal lobe in the human brain.

There are several proposals of executive functions, for example, inhibition, working memory, planning, monitoring, emotional regulation, organization of materials, initiative, verification, internal language regulating behavior, metacognition, behavioral regulation, and cognitive flexibility; among others [8]. At present there is no absolute consensus on the number of executive functions that should exist, but there is agreement that we are referring to mental abilities that allow the conscious regulation of behavior [9].

Regarding the rehabilitation processes of executive functions, there is currently no complete development of this process, since the rehabilitation proposals are from recent years and are based on traditional pencil and paper processes [10, 11]. In this sense, it is of great importance to identify what technological developments have been proposed to rehabilitate executive functions for human beings suffering frontal damage [12].

Therefore, a contribution to the current state of the art of neuropsychology research is to identify the new proposals that are being developed for the rehabilitation of executive functions. In this sense, a systematic review of recent technological developments for the rehabilitation of executive functions is presented below.

2 Method

The present investigation was carried out by means of a systematic review methodology of the collection of 13 academic articles [13–25]. The present study was carried out through two processes: (a) first, the inclusion and exclusion criteria of the articles to be included in this review were determined; (b) then, a protocol was elaborated to analyze the information of the selected articles to achieve the objective of identifying the devices developed to stimulate and rehabilitate executive functions.

2.1 Inclusion and Exclusion Criteria

Inclusion: The article develops or analyzes a technological device to stimulate or rehabilitate the executive function. It is an article with the participation of human beings and measurement of the developed device.

Exclusion: The article analyzes a paper and pencil or traditional procedure, without technological elements, to stimulate or rehabilitate executive functions. The article develops another procedure which are not stimulate or rehabilitate, such as, assessment executive functions.

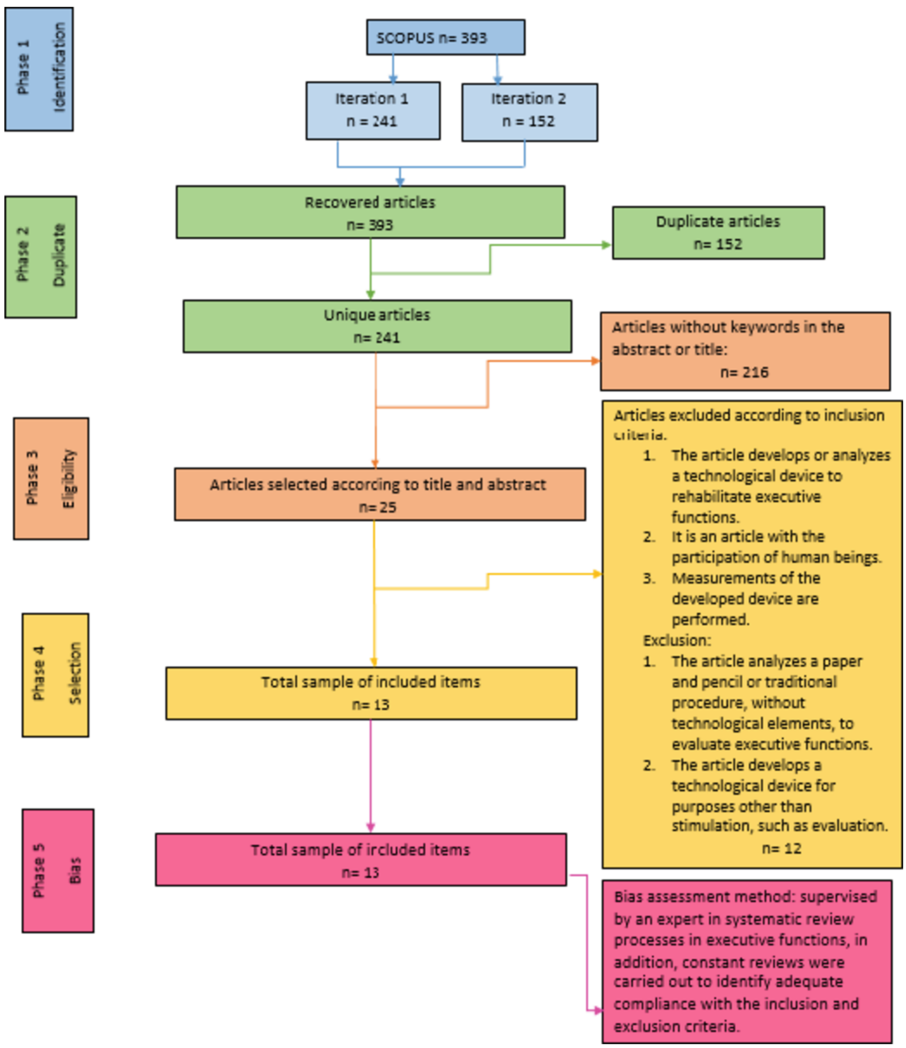

Fig. 2. Systematic review followed in this research.

In order to carry out this systematic review, it was necessary to complete 5 stages (see Fig. 2):

A. Identification stage: a search for academic articles was carried out in the Scopus metabase and main journals in the context of psychology. Scopus was used, due to its importance in the Latin American context, in addition to the fact that it is a meta-base that offers greater precision when considering time ranges and provides a large number of articles of great scientific prestige. The temporal range was papers published between 2015 and 2023, using keywords in the English and Spanish languages "executive functions, technology, rehabilitation, stimulation, psychology, frontal lobe".
B. Duplicate stage: duplicate articles were deleted.
C. Eligibility stage: inclusion and exclusion criteria were determined to obtain relevant data that contribute to the research objective.
D. Selection stage: the articles were downloaded to be read completely and by applying the inclusion and exclusion criteria, the articles linked to the study were selected.
E. Bias stage: the whole process was supervised by an expert in systematic review processes in executive functions, and constant revisions were made to identify the adequate fulfillment of the inclusion and exclusion criteria in the analysis of the articles worked on in the research.

3 Results

Statistical analyses were performed with the 13 studies that met the criteria for inclusion in the study [13–25]. All the data analyzed for the 13 scientific articles statistically analyzed are shown in appendix 1. In reference to the average number of participants found in the studies, a mean sample size M = 65.77 (SD = 61.95) was identified. In most of the studies a frequency between 0 and 50 participants was found. The data can be seen in Fig. 3.

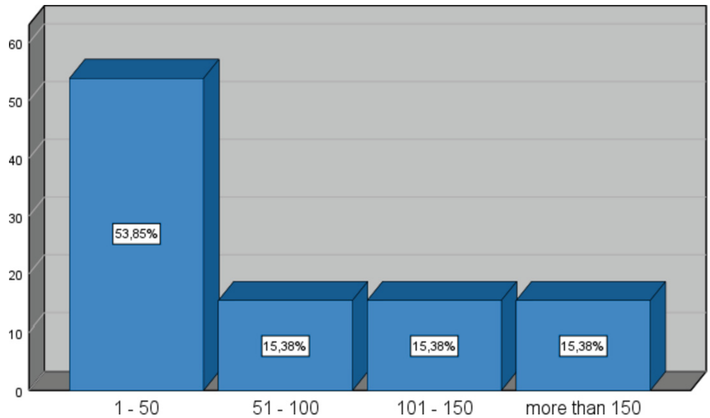

Fig. 3. Study sample size ranges.

In relation to the countries that have developed technological developments that help stimulate and rehabilitate executive functions, it was found that Italy is the country with the most developments in this regard. Figure 4 shows the results.

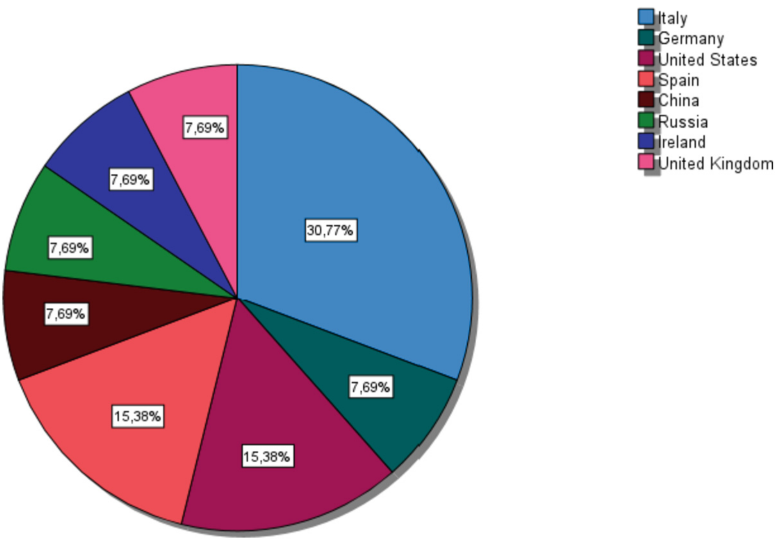

Fig. 4. Countries that have generated technology to stimulate or rehabilitate executive functions.

When observing the educational level of the participants, it was found that most of the studies did not specify this criterion in their articles. Figure 5 shows the different educational levels of the participants in the different studies.

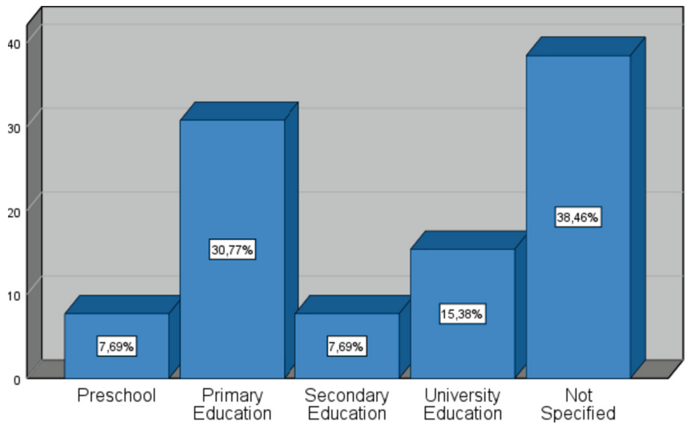

Fig. 5. Educational level of participants.

In relation to the type of population that participated in the studies with technological developments for the stimulation and rehabilitation of executive functions, it indicates that in most of the investigations adults with some disorder were chosen. Figure 6 shows the different types of populations with which the studies worked.

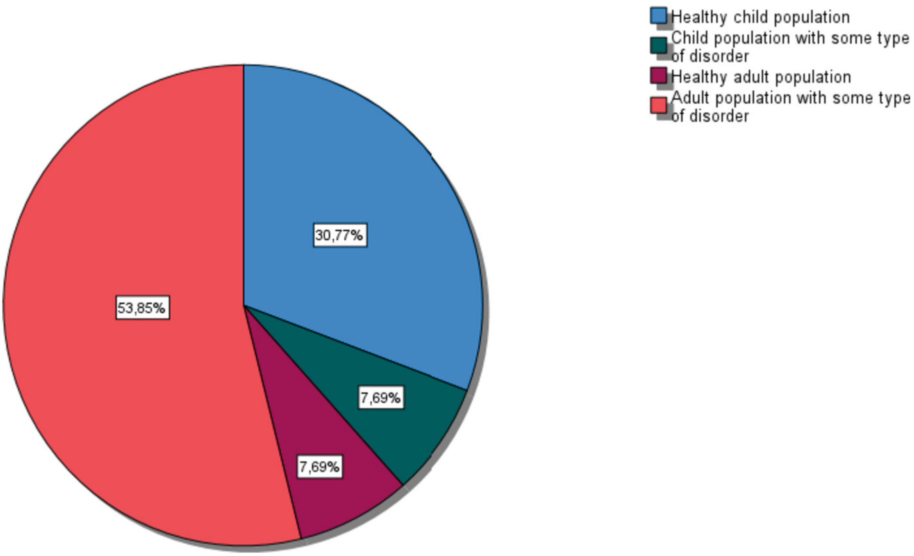

Fig. 6. Characteristics of the participants.

The following technological developments were found in the 13 studies [13–25]: (a) Bee-Bot Robot, which is a bee-shaped device that is used in an ER-Lab, where children must complete goals programmed by the Bee- Bot Robot [13]; (b) CortexVR, is an application with different virtual reality games to stimulate executive functions that must be complemented with the CoachApp for training [14]; (c) Computer-based training, composed of working memory and mathematical tasks, for this training 3 stages need to be fulfilled in order to measure the stimulation performed [15]; (d) Computer Aided Technology (CAT), which is a specialized training program for each patient performed by doctors specialized in rehabilitation [16]; (e) Smartwatch Executive Function Supports, is an application for the Smartwatch that allows patients with ID and ASD to schedule appointments and stimulate or rehabilitate their planning [17]; (f) Brain-Computer Interface + Exoskeleton Technology in Complex Multimodal Stimulation (BCNI), 3 mental commands are given on the computer screen and with the help of exoskeleton technology the patient is rehabilitated; (g) LEGO Mindstorms EV3, is a programmable robotic kit in which children must assemble and program the robot to do certain activities that increase in difficulty [19]; (h) Ozobot, is a small educational robot, which is coded to follow colors on a linear surface, then children must use the colors to solve what they are asked [20]; (i) CityQuest, is a virtual reality game of a city, where patients must navigate avoiding obstacles [21]; (j) The use of a wearable camera to record significant events over 6 weeks to help Alzheimer's patients [22]; (k) Eye-tracking technology, is a computerized version of the Tower of Hanoi, where they have a limited number of movements to solve the instructions [23]; (l) A set of 3 robots and a sensor-based device, which focused on interactive games with force support assisted by the 3 robots [24]; (m) Bimodal VR-Stroop, which is a virtual reality game that has two scenarios that has visual and auditory distractors, where the person must read the color that is written on the screen, not with the color with which it is written.

Based on the limitations of the studies analyzed, it was found that most of them are superficial investigations or they do not present limitations in the published article. Figure 7 shows the results of this analysis.

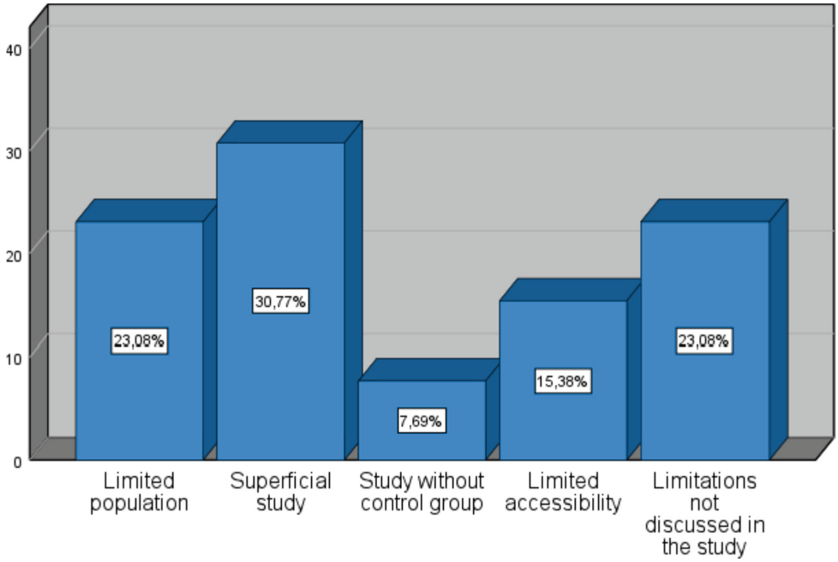

Fig. 7. Limitations of the studies analyzed

In the research analyzed, it was found that they focus on rehabilitating various executive functions, among which working memory and problem-solving skills stand out. Figure 8 shows the executive functions worked on in each study.

In relation to the time required for rehabilitation with the different technological devices, it was found that the most predominant time to stimulate or rehabilitate the patients was from 1 to 5 weeks. Figure 9 shows the ranges of time required to rehabilitate patients.

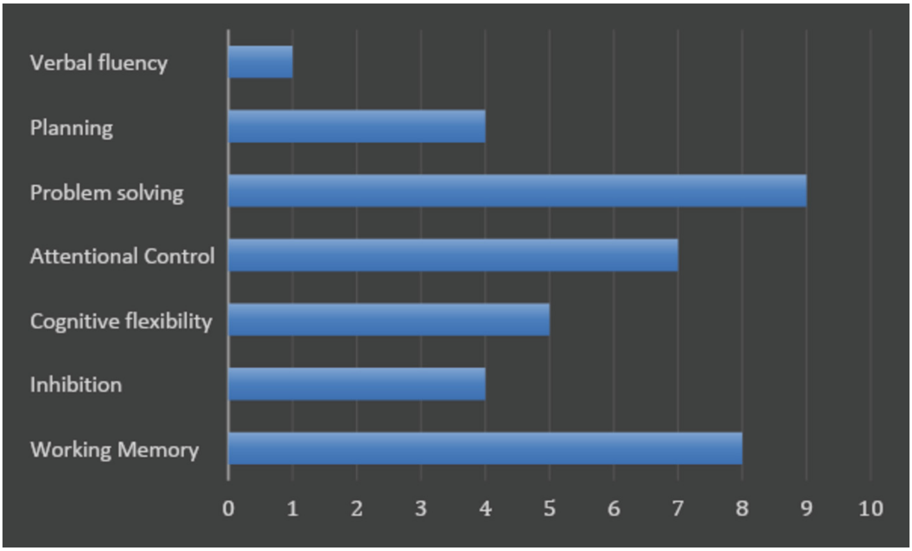

Fig. 8. Executive functions stimulated in the technological developments reviewed

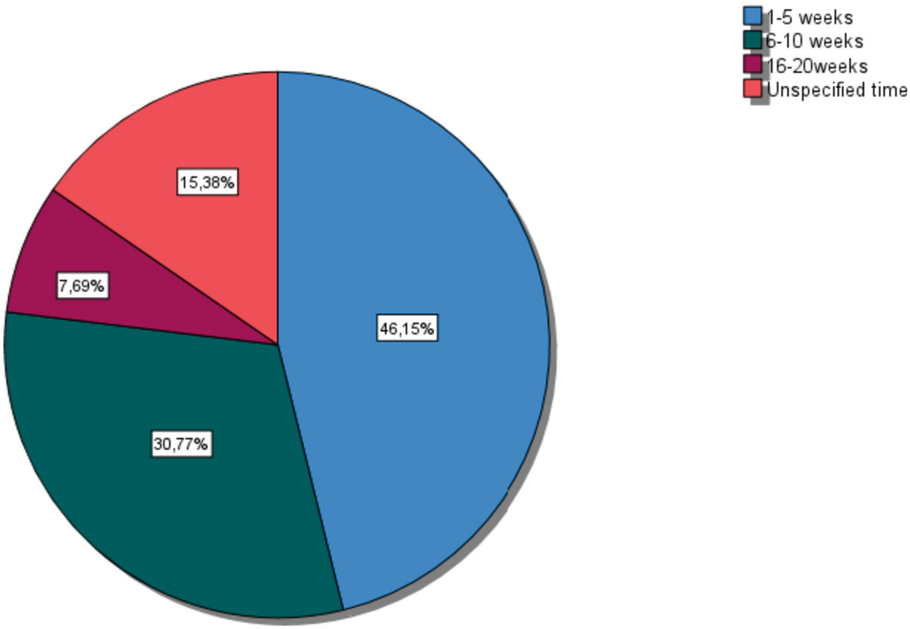

Fig. 9. The ranges of time required to rehabilitate or stimulate patients.

4 Conclusions

In this article we have reported an investigation that conducted a systematic review of the technological developments that exist to rehabilitate executive functions. The essential contribution of this study to the line of research on executive functions has to do with the identification of technological resources for the neuropsychological treatment of these mental abilities, which is a topic that is still under construction.

In the extraction of results from the analyzed studies, the following technological tools were found to stimulate and rehabilitate executive functions: Bee-Bot Robot, CortexVR, Computer Based Training, Computer Aided Technology, Smartwatch Executive Function Supports, Brain-Computer Interface + Exoskeleton Technology in Complex Multimodal Stimulation, LEGO Mindstorms EV3, Ozobot, CityQuest, use of a wearable camera to record more significant events, Eye Tracking Technology and Bimodal VR-Stroop.

The main benefit of having technological tools to stimulate and rehabilitate executive functions is based on the fact that the patient who needs this type of attention can feel that he/she is carrying out activities that are consistent with the technological world in which we live today [26]. The implementation of technology in the rehabilitation or stimulation of executive functions can be very useful for patients, because nowadays technology is part of everyday life and in the case of children or younger patients this alternative optimizes the intervention. On the other hand, the use of technological devices can be a challenge with older adults, which is why it is necessary in some cases to make a digital literacy and pre-training [27].

In a future research project, we plan to create a technological application that allows us to rehabilitate the executive functions of children, adolescents and adults who present deficiencies in these mental abilities. In addition, it is of interest to conduct experimental studies in which, through pre- and post-test analysis, we can determine the effectiveness of the technological devices analyzed in this article.

Appendix 1

Title	Sample	Research countries	Ed. Level	Population type	Technological development	How is it used?	Limitations	Executive functions stimulation	Intervention time
Empowering Executive Functions in 5- and 6-Year-Old Typically Developing Children Through Educational Robotics: An RCT Study	187	Italy	Preschool students	Children between 5 and 6 years of age, who are studying in a school	Bee-Bot robot, bee-shaped device with boards or complementary material	It is used in an ER-lab, where children must complete goals programmed by the BEE-Bot robot. As this robot has buttons to move forward, stop, delete the memory, etc., the children must use these buttons according to the goals to be accomplished	It is important that you are in a school or classroom environment	Mamory of visuospatial work, inhibition, self-control, cognitive flexibility, sustained attention, problem solving	20 training sessions of 60 min each
CortexVR: Immersive analysis and training of cognitive executive functions of soccer players using virtual reality and machine learning	37	Germany	Don’t specify	Men and women from 21 to 35 years old	CortexVR, is an application with different virtual reality games	By means of virtual reality glasses, the CortexVR application is used, which has some game modes (player tracking, counting players, finding the ball), then, while people play, they stimulate some executive functions. Similarly, it should be complemented with the CachApp for training and analysis	The full benefits of this adaptation are not yet fully known	Inhibition, working memory, cognitive flexibility, reasoning and problem solving	It does not show an exact time, but you must play the 3 game modes in a specific order and repeat it 4 times

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Title	Sample	Research countries	Ed. Level	Population type	Technological development	How is it used?	Limitations	Executive functions stimulation	Intervention time
Smartwatch Executive Function Supports for Students With ID and ASD	3	United States	University	Patients with a diagnosis of intellectual disability and autism spectrum disorder	A smartwatch app to help support executive functions	It is an application that requires students to be digitally literate, so that they can enter the alarms of their appointments through an appointment formula and through the Smartwatch access the information. With the purpose of helping the student to have more independence	The application does not allow selecting the date of the appointment, only the day of the week. In addition, as the study sample was very limited, it is not possible to ensure that it works for other age groups	Planning, organization and independence	3 sessions per week of 50 min. Each one
Educational robotics to develop executive functions visual spatial abilities, planning and problem solving	30	Italy	5th grade of primary education	Healthy children attending school	LEGO Mindstorms EV3. It is a programmable robotic kit, created by Lego	The children have to assemble the robot, then they are given programs, which they have to program and they increase in difficulty. In addition, the children can observe the movements of the toy and what it does according to the environment in which it is	Don’t specify	Visuospatial attention, planning, problem solving, working memory, control of complex tasks	10 meetings, 2 h each and one meeting per week

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Title	Sample	Research countries	Ed. Level	Population type	Technological development	How is it used?	Limitations	Executive functions stimulation	Intervention time
Computer-based training in math and working memory improves cognitive skills and academic achievement in primary school children: Behavioral results	104	Spain	Primary Education	Children from 7 to 12 years old in rural schools in Murcia (Spain)	Computer-based training, consisting of: working memory and mathematical tasks	This training consists of 3 phases: pre-training, training and post-training. Through tasks of mathematical ability, reading, and verbal skills. In order to measure the stimulation, a test is performed before and after the training	Therefore, it is not possible to measure long-term effects because the post-training measurement is a short-term measurement	Working memory, adaptability, inhibition	17 weeks
Computer aided technology-based cognitive rehabilitation efficacy against patients' cerebral stroke	128	China	10 a 11 years of basic education	Cardiovascular accident patients, 18 to 80 years old	Computer Aided Technology (CAT)	Doctors specialized in rehabilitation have designed a specialized training program for each patient, so in addition to the one-on-one training with the patient, CAT is applied and the respective medication for each patient	Because MOCA is used for rehabilitation assessment, there may be certain limitations and misdiagnoses	Memory, visual and spatial executive function, abstract ability, orientation and language	4 weeks, 30 min per day, 6 days per week
Use of a Brain–Computer Interface + Exoskeleton Technology in Complex Multimodal Stimulation in the Rehabilitation of Stroke Patients	44	Russia	Don't specify	Patients with cardiovascular stroke, 61 years of age	Brain–Computer Interface + Exoskeleton Technology in Complex Multimodal Stimulation (BCNI)	The patient is seated in a chair in front of a computer with both wrists attached to an exoskeleton. Then on the screen comes out 3 mental commands: relax, imagine the state of the muscles when opening the right or left hand. The hand opens after the system recognized the correct classification of execution	Patients only have an average capacity and tolerance of 20 to 30 min	Problem solving, visuospatial thinking, attention, working memory (practice)	8 to 10 procedures, 10 min per session, with a 3 to 5 min break

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Title	Sample	Research countries	Ed. Level	Population type	Technological development	How is it used?	Limitations	Executive functions stimulation	Intervention time
Enhancing the potential of creative thinking in children with educational robots	171	Italy	4th and 5th year elementary school students	Children	Ozobot, a small educational robot	It is a robot that is coded to follow colors on a linear surface, so the children use the colors to determine the robot's movements according to the instructions they receive	Don't specify	Problem-solving, visuospatial thinking, attention, working memory	There is no time limit, it depends on how long the children take
"CityQuest," A Custom-Designed Serious Game, Enhances Spatial Memory Performance in Older Adults	56	Ireland	Don't specify	Healthy older adults 65 years of age and older	CityQuest, a virtual city game	A virtual game that through navigation of unfamiliar and crowded locations that require participants to control navigation through city spaces and avoid obstacles	Don't specify	Spatial memory, working memory, problem-solving, sustained attention, cognitive flexibility	2 sessions per week of 60 min, for 5 weeks
Using a wearable camera to support everyday memory following brain injury: A single-case study	1	United Kingdom	Don't specify	A 48-year-old man with Alzheimer's disease	Handheld Camera	The use of a wearable camera to record significant events over a 6-week period to aid memory recall	It was only a case study, so we need to deepen the effectiveness with a larger sample	Working memory	6 weeks
Reading Goals and Executive Function in Autism: An Eye-Tracking Study	22	Spain	School and high school	Middle-class children and adolescents with a diagnosis of autism	Eye-tracking technology	Using a computerized and modified version of The Tower of Hanoi, they must read the instructions on the screen and solve the problem with a maximum of 15 moves per problem, moving the computer mouse to do so. While the eye tracker evaluates it	Its application cannot be generalized to the entire population with autism	Problem solving, inhibition, planning	40 min

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Title	Sample	Research countries	Ed. Level	Population type	Technological development	How is it used?	Limitations	Executive functions stimulation	Intervention time
Robotic Rehabilitation: An Opportunity to Improve Cognitive Functions in Subjects With Stroke. An Explorative Study	51	Italy	Less than 26 years of education	Persons between 35 and 85 years of age, who have had a cardiovascular accident in the last 6 months	A set of three robots and a sensor-based device for upper limb rehabilitation	The rehabilitation program focused on interactive games, carried out with the support of the assistance forces provided by the 3 robots (Amadeo, Pablo and Diego)	Lack of a control group in the application of robots	Planning, problem-solving, selective attention, cognitive flexibility	30 rehabilitation sessions, 45 min each, 5 days a week
Application of virtual environments in a multi-disciplinary day neurorehabilitation program to improve executive functioning using the Stroop task	21	United States	Don't specify	Brain-injured patients with executive dysfunction	Bimodal VR-Stroop	It consists of two scenarios (a classroom and an apartment), then in both there are visual and auditory distractions that appear for 5 s, in intervals of 10, 15 and 25 s. The task is to say the color that comes up, not the color it is written in	Excludes patients who lack the cognitive sufficiency to participate in tasks	Sustained attention, attention to visual details, cognitive flexibility	Sessions 1 and 8 of 60 min; Sessions 2 to 7 of 30 min

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