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Working Memory Training in children with attention deficit hyperactivity disorder: A systematic review

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Abstract

Working memory training may help children with attention deficit hyperactivity disorder (ADHD), but robust evidence from systematic reviews is lacking. Children with poor Working memory ability struggle with academic and cognitive work compared to similar-aged peers without working memory deficits. Besides, working memory is correlated with inattention and disorganization in those with ADHD. The aim of this systematic review was to assess the effect of working memory training on symptoms and behaviors of children with ADHD. A search equation was proposed (ADHD OR attention deficit hyperactivity disorder AND working memory training), with twenty-four studies meeting the inclusion criteria in the Clarivate Analytics Web of Science Core Collection database. A bibliometric analysis was conducted to identify the importance of the research topic and a citation network was built to establish the lines of research. Finally, the citation network was exported to Gephi to visualize the research groups studying the topic. Findings suggest 3 lines of research: (a) Effects of working memory training on working memory, and academic performance in children with ADHD, (b) Effects of working memory training on executive functioning and child ADHD related symptoms, (c) Effects of working memory training on brain activity in child ADHD. Implications for clinical practice and school-based interventions are discussed.
Keywords: ADHD; working memory training; executive functioning; academic performance.

Resumen

Entrenamiento de la Memoria de Trabajo en niños con trastorno de atención e hiperactividad: Una Revisión sistemática. El entrenamiento de la memoria de trabajo puede ayudar a los niños con trastorno por déficit de atención e hiperactividad (TDAH), pero faltan pruebas sólidas de revisiones sistemáticas. Los niños con una capacidad de memoria de trabajo deficiente tienen dificultades en el trabajo académico y cognitivo en comparación con sus compañeros de edad similar sin déficits de memoria de trabajo. Además, la memoria de trabajo se correlaciona con la falta de atención y la desorganización en aquellos con TDAH. El objetivo de esta revisión sistemática fue evaluar el efecto del entrenamiento de la memoria de trabajo en los síntomas y comportamientos de los niños con TDAH. Se empleó una ecuación de búsqueda (TDAH O trastorno por déficit de atención e hiperactividad Y entrenamiento de la memoria de trabajo), que halló veinticuatro estudios que cumplieron los criterios de inclusión en la base de datos de la colección central de la Web of Science de Clarivate Analytics. Se realizó un análisis bibliométrico para identificar la importancia del tema de investigación y se construyó una red de citas para establecer las líneas de investigación. Finalmente, la red de citas se exportó a Gephi para visualizar los grupos de investigación que estudian el tema. Los resultados sugieren 3 líneas de investigación: (a) Efectos del entrenamiento de la memoria de trabajo sobre la memoria de trabajo y el rendimiento académico en niños con TDAH, (b) Efectos del entrenamiento de la memoria de trabajo sobre el funcionamiento ejecutivo y los síntomas relacionados con el TDAH infantil, (c) Efectos del entrenamiento de la memoria de trabajo sobre la actividad cerebral en el TDAH infantil. Se discuten las implicaciones para la práctica clínica y las intervenciones escolares.
Palabras clave: TDAH; entrenamiento de la memoria de trabajo; funcionamiento ejecutivo; rendimiento académico.

Attention Deficit Hyperactivity Disorder (ADHD) is a life-span neuropsychiatric disorder with core symptoms of inattention, hyperactivity, and impulsivity (Anker et al., 2019). Approximately 9.4% of children aged 2 to 17 (6.1 million children) have been diagnosed with ADHD and this prevalence rate has continued to increase over time for both females and males (Wong & Landes, 2022). Previously, others found that in 2010, compared to females, males had higher prevalence of ADHD among Whites (7.7% for males and 3.2% for females),

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Blacks (5.9% and 2.2%), Hispanics (3.8% and 1.1%), and Asian/Pacific Islanders (1.2% and 0.6%) (Getahun et al., 2013).

The impairing condition in children with ADHD profoundly affects academic performance, social interactions, and well-being (Chen et al., 2022). Various cognitive alterations are also characteristic of the condition (Bölte et al., 2018) . Deficits in executive functions are central in ADHD, affecting verbal and spatial working memory (WM) (Landínez Martínez & Montoya Arenas, 2021b), planning, attention, and vigilance (Sergeant, 2004). Other prominent cognitive impairments include temporal processing, inhibition (Sonuga-Barke et al., 2010), emotional dysregulation (Shaw et al., 2014), the preference of small immediate rewards (Marx et al., 2021), and impaired overall decision making (Sonuga-Barke et al., 2016).

The traditional treatment of ADHD mostly uses pharmacological intervention to improve attention and alleviate hyperactive impulse and other explicit behavior by regulating the transmission of signal factors between synapses (Ng, 2017). However, the use of stimulants increases the risk of anorexia, weight loss, and insomnia (Briars & Todd, 2016). Although medication is efficacious in randomized controlled trials (RCT) in the short/ medium-term and is indicated as the first-line treatment (Taylor et al., 2004), it has a number of potential limitations-each affecting some patients. These include: partial response or nonresponse (Cortese et al., 2018); possible adverse effects (Cortese et al., 2013); uncertainty about long-term costs and benefits (Molina et al., 2009); poor adherence (Adler & Nierenberg, 2010); and negative medication-related attitudes from patients, parents, or clinicians (Cortese et al., 2015).

In recent years, WM training has been investigated as a potential ADHD treatment (Landínez-Martínez & Montoya-Arenas, 2021a). It involves the use of brain games, targeting different cognitive skills, including attention, concentration, verbal and visual WM, processing speed, and inhibition (de Oliveira Rosa et al., 2020a). Using a model that is adaptive in nature (i.e., the activity increases or decreases in difficulty, depending upon a student's performance), WM training programs have demonstrated performance gains in various cognitive and WM tasks after 20 hours of intervention (Wiest et al., 2020), with maintained improvements observed over a six-month period (Gathercole et al., 2019). Specifically, n-back tasks have been shown to decrease WM deficits over time (Jones et al., 2020a).

WM training offers one potential intervention approach. Studies examining WM training have revealed promising results, demonstrating greater performance improvements in such academic skills as reading (Holmes & Gathercole, 2014) and math (Dahlin, 2013a). Variability exists in effectiveness of transfer effects (from WM training to academic performance) depending on such factors as duration of training (Schwaighofer et al., 2015), baseline performance (Johann & Karbach, 2020), sleeper effects (Klahr et al., 2011), supervision during training (Schwaighofer et al., 2015), the addition of game elements to training tasks (Johann & Karbach, 2020), motivation (Diamond, 2014), and the types of academic skills measured (Holmes & Gathercole, 2014). This inspired us to focus on the main characteristics of WM training and how it impacts the quality of life and psychological well-being in ADHD.

The aim of this systematic review was to assess the effect of working memory training on symptoms and behaviors of children with ADHD.

Method

A bibliometric analysis was performed on 123 manuscripts extracted from the Clarivate Analytics Web of Science Core Collection database to observe the evolution of the scientific literature and identify specific characteristics of the related knowledge domain. The bibliometric analysis was integrated with a literature review using a method comparable to the method employed in another study (Valencia-Hernández et al., 2020). The rationale behind this approach is to use scientometrics techniques and citation analysis.

First, the Web of Science database was selected to identify articles that describe the proposed search equation: TOPIC:(ADHD) OR TOPIC: (Attention deficit hyperactivity disorder) AND TOPIC: (working memory training) from 2000 to 2022 (Vallaster et al., 2019). The search equation file was then converted to txt for further analysis. Then, a bibliometric analysis identified the importance of the research topic in the current literature (Zupic & Čater, 2015). To do this, the bibliometrix tool was used (http://www.bibliometrix.org). Third, a citation network was built in order to establish the study research lines. This algorithm is based on the graph theory, where studies are represented as nodes and citations as links. So, every node is a knowledge unit in the network. The citation network was built through Sci2 tool software and then every referenced citation was chosen to identify articles with a 95% similarity through the Jaro-Wikker algorithm and to be able to remove duplicates (Jaro, 1989; Prasetya et al., 2018). Finally, the citation network was updated through merge node. Overall, the search equation was converted in a citation network that comprises both the selected articles and its references (Gomez, 2020).

Lastly, the citation network was exported to Gephi (Bastian et al., 2009) to be visualized into groups (author communities). Besides, in-degree, out-degree, and betweenness filters were analyzed to investigate the structure of the network and to calculate the main parameters (node connectivity, positioning, and citation). Then, the giant component was computed. This is a group of nodes (articles) that are all connected to each other. Disconnected nodes from the main network were removed (Gomez, 2020). Finally, both a clustering algorithm (Blondel et al., 2008) and the modularity index were applied to the final citation network. This approach assembled densely-connected nodes to the main research perspectives. The final citation network is composed by three clusters (Figure 1).

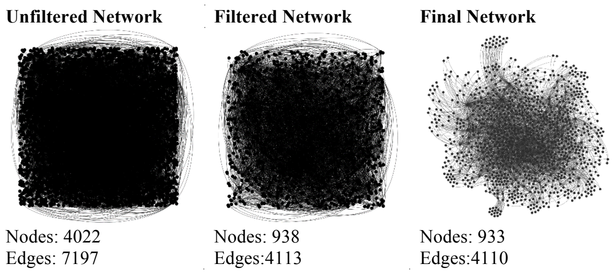
Elegibility criteria

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (www.prisma-statement.org) (Moher et al., 2009) were used to identify studies to include in the Systematic Review. (See flow diagram for inclusion and exclusion criteria). The authors checked 933 articles from the citation network and selected 24 studies according to the inclusion and exclusion criteria (see figure 2 & Table 1).

Statistical inclusion criteria

1. Articles with a similarity level of the text less than 95% according to the Jaro-Winkler algorithm (non-duplicate articles).
2. The Modularity Class algorithm was applied to the citation network and cluster nodes equal or higher than 10% were selected. Three clusters met these criteria and depict three research perspectives about working memory training in ADHD (see figure 4).
3. The most highly-cited papers according to In-degree, Out-degree and Betweenness centrality ranks.

Figure 1. Citation network transformation

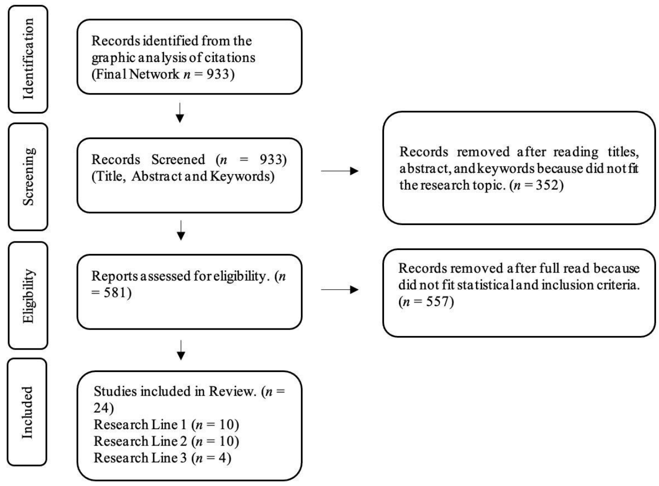


Source: Author

General inclusion criteria

4. Longitudinal and cross-sectional papers (Systematic Reviews, Meta-analysis)
5. Papers focused on working memory training in childhood ADHD

Figure 2. Eligibility criteria Flow diagram



Results

The studies included in the systematic review can be seen in Table 1.

Table 1. Studies Included in the Systematic Review

Study	Sample size		Age (mean)		Control Group	Testing		Outcome measure	Duration (weeks) and sessions	Training	
	Exp	Ctrl	Exp	Ctrl		Immediate follow-up	Delayed follow-up			Version	Site
Bergman-Nutley & Klingberg. (2014)	176	304	11.1	11.0	Passive	5 weeks	none	OOO/FI/Math test	May-25	Cogmed	School/Home
Nelwan & Kroesbegen. (2016)	21	19	11.03	10.86	Active	8 weeks	16 weeks	Lion game, Monkey game, BRIEF	16/64	Jungle Memory	School
Söderqvist & Bergman-Nutley. (2015)	20	22	9.85	9.77	Passive	5 weeks	2 years	SNST/OOO/FI/ Math test	May-25	Cogmed	School
Nelwan et al., 2018	23	21	10.68	11.11	Active	8 weeks	16 weeks	Lion game, Monkey game/ Arithmetic Tempo Test	16/64	Jungle Memory	School
Söderqvist et al., 2012	22	19	9.68	9.81	Active	5 weeks	1 year	WSB/WSF/ OOO/Block Design/RCM/ PIRLS/ PNWRT/	May-25	Cogmed	School/Home
Dahlin, 2011	42	15	10.0	10.3	Passive	5 weeks	7 months	DSF/DSB/ Stroop/OVT	May-25	Robomemo	School
Dahlin, 2013	21	21	10.7	10.7	Passive	5 weeks	7 months	BNST/DSF/DSB/ VSWM/RCM	May-25	Cogmed	School
St Clair Thompson et al., 2010	117	137	6.10	6.11	Passive	8 weeks	5 months	DSF/Block recall/LRT/ FI/ MAT/ WISC-IV/ GRT/ Mental mathematics	Aug-16	Memory booster	School
Wiest et al., 2022	43	none	11.7	none	none	4 weeks	none	IVA-2/ WRAML-2/ WISC-V	Apr-20	Captain´s Log program	Clinical setting
Studer-Luethi et al., 2022	43	43	10.1	10.1	Active	6 weeks	none	JAT/AST/PTT/ CFT20-R/BCRT/ GVIT/ GRDT	6/17.6	The jumping animal task & The farmer task	School

Study	Sample size		Age (mean)		Control Group	Testing		Outcome measure	Duration (weeks) and sessions	Training	
	Exp	Ctrl	Exp	Ctrl		Immediate follow-up	Delayed follow-up			Version	Site
Chacko et al., 2018	44	41	8.4	8.4	Active	4 weeks	none	AWMA/ DBDRS/IRS	May-25	Cogmed	Home
Beck at al., 2010	25	24	11.7	11.7	Passive	5 weeks	4 months	BRIEF/CPRS/ CTRS	May-25	Robomemo	Home
Chacko et al., 2014	44	41	8.4	8.4	Active	5 weeks	none	DBRS/AWMA/ A-X CPT/ WRAT4-PMV	May-25	Cogmed	Home
Green et al., 2012	12	14	9.9	9.6	Active	5 weeks	none	RAST/CPRS	May-25	Cogmed	School
Bigorra et al., 2016	21	15	8.7	9.0	Active	5 weeks	6 months	BRIEF/CPRS/ CTRS/CBCL/ SDQ/WFIRS-P/ DSB/LNS/ VSWM/CPTII/ TOL/WCST/ TMTB	May-25	Robomemo	Home
Dongen-Boomsma et al., 2014	26	21	6.5	6.6	Active	5 weeks	none	ADHD-RS/ ADHD-RS-T/ BRIEF/ADS/ KC/Sentences/ RCPM/ DNS/ SADT/SS/CGI-I	May-25	Cogmed (JM)	Home
Holmes et al., 2010	12	13	9.9	9.9	Active	5 weeks	6 months	AWMA	May-25	Cogmed	School
Capodieci et al., 2018	18	16	5.4	5.4	Passive	8 weeks	none	CTRS/DSF/DSB/ SWMT/WNWT/ MFT-14	Aug-16	Working Memory Control Intervention Program	School
Muris et al., 2018	28	20	9.6	11.4	Active	5 weeks	1 year	ADHD-Q/ SDQ/ BRIEF/DSF/ DSB/CBTT/ SIT/BT	May-25	Cogmed	School/Home
Jones et al., 2020		39	10.2	10.0	Active	5 weeks	3 months	N-back task / CPT II/BRIEF/ CBCL/ CPRS	May-20	Cogmed	School/Home
Hoekzema et al., 2010	10	9	10.0	10.0	Active	12 weeks	none	CPRS/CTRS/ SAT/GO-NoGo	Dec-60	Working memory training program	Ambulatory setting
Hoekzema et al., 2011	10	8	11.2	8.1	Active	2 weeks	none	SIT	2-Oct	Working memory training program	Ambulatory setting
Stevens et al., 2016	18	18	12.1	11.1	Active	5 weeks	2 weeks	CPT II/WISC-IV	May-25	Cogmed	School
De oliveira rosa et al., 2020	10	10	10.9	11.9	Active	12 weeks	none	N-back task/ SADT/ GO-NoGo	Dec-48	ACTIVATE	School

Note. OOO = Odd One Out; FI = Following Instructions; BRIEF = Behavior Rating Inventory of Executive Function; SNST = Swedish National Standardized Tests; WSB = Word span backwards; WSF = Word span forwards; RCPM = Raven's Colored Progressive Matrices; PIRLS = Progress in International Reading Literacy Study; PNWRT = Phonological non-word reading test; DSF = Digit span forward; DSB = Digit span backwards; OVT = Orthographic verification test; BNST = Basic Number Screening Test; VSWM = Visuo-Spatial Working memory Span Board; LRT = Listening Recall Task; MAT = Mental Arithmetic Task; GRT = Group Reading Test II; WISC-IV = Arithmetic subtest Wechsler Intelligence Scale for Children; IVA-2 = Integrated Visual and Auditory Continuous Perform Test; WRAML-2 = Wide Range Assessment of Learning and Memory; JAT = Jumping Animal Task; AST = Animal Span Task; PTT = Perceptual Training Tasks; CFT 20-R = Culture Fair Intelligence Test; BCRT = Backward Color Recall Task; GVIT = German vocabulary intelligence test; GRDT = German reading diagnostic test; AWMA = Automated Working Memory Assessment; DBDRS = Disruptive Behavior Disorder Rating Scale; IRS = Impairment Rating Scale; CPRS = Conners' Parent Rating Scale– Revised: Short Form; CTRS = Conners' Teacher Rating Scale–Revised: Short Form; A-X CPT = The A-X Continuous Performance Test; WRAT4-PMV = Wide Range Achievement Test 4 Progress Monitoring Version; RAST = The Restricted Academic Situations Task; CBCL = Child Behavior Checklist; SDQ = Strengths and Difficulties Questionnaire; WFIRS-P = Weiss Functional Impairment Rating Scale For Parents; LNS = WISV-IV Letter-Number Sequencing; CPT II = Commission errors of Conners' continuous performance test; TOL = Tower of London; WCST = Wisconsin card sorting test; TMTB = Trail Making Test B; ADHD RS = ADHD Rating Scale; ADHD RS-T = ADHD Rating Scale Teachers; ADS = Adapted digit Span; KC = Knox Cubes LDT; DNS = Day-Night Stroop; SADT = Sustained Attention Dots Task; SS = Shape School; CGI-I = The Clinical Global Impressions-Improvement; SWMT = Selective Working Memory Test; WNWT = Walk -No Walk Test; MFT-14 = Matching Figures Test; ADHD-Q = ADHD questionnaire; CBTT = Corsi Block Tapping Task; SIT = Stroop Interference Task; BT = Bourdon-Vos Test; SAT = Selective Attention Test.

Graphic Analysis of citations and main research lines

Figure 3 shows the citation network about WM training in children with ADHD. This network suggests three main clusters (≥10%), which depict 43.73% of the final graph. Every cluster gathers a set of references according to a research line. Nodes represent articles and edges represent citations. The first research line (purple) represents 19.61% of the graph and is focused on the effects of WM training on working memory, and academic performance in children with attention deficit hyperactivity disorder. The second research line (green) represents 12.97% of the graph and the focal point is the effects of working memory training on executive functioning and child ADHD related symptoms. The third research line (blue) represents 11.15% of the graph and is focused on the effects of working memory training on brain activity in child attention deficit hyperactivity disorder.

Figure 3. Citation network in Working Memory Training in children with ADHD.

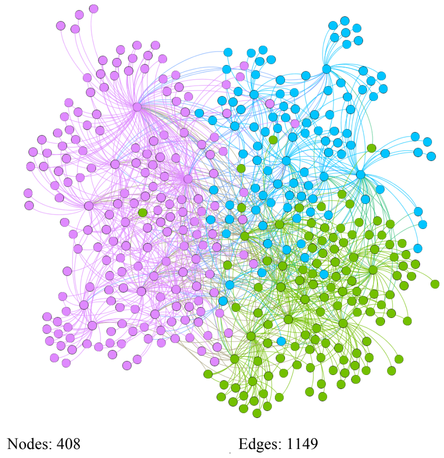
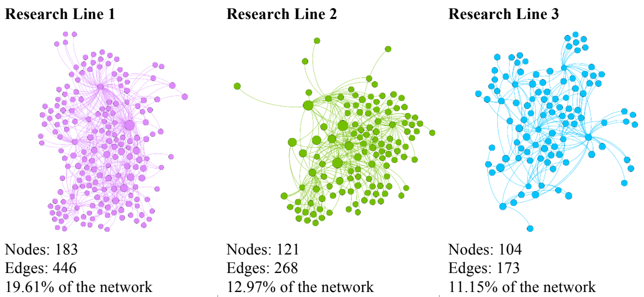


Figure 4. Graphs of the three Research Lines



Effects of working memory training on working memory, and academic performance in children with attention deficit hyperactivity disorder (main outcomes)

Table 2. Studies included in the first Research Line

Study	Main Outcomes
(Bergman-Nutley & Klingberg, 2014)	The training group improved significantly more than the control group on all transfer tests ($p < .0001$). The effect size for mathematics was small ($d = .20$) and the effect sizes for the WM tasks were moderate to large (.65).
(Nelwan & Kroesbergen, 2016)	Bayesian analyses showed possible short-term effects of JM on near transfer measures of verbal WM, but none on visual WM. Children that received JM first, performed better after MT than children who did not train with JM at all.
(Söderqvist & Bergman Nutley, 2015)	At grade 6, reading improved to a significantly greater extent for the training group compared to the control group (medium effect size, Cohen's $d = .66$, $p = .045$). For math performance the same pattern was observed with a medium effect size (Cohen's $d = .58$) reaching statistical trend levels ($p = 0.091$). Moreover, the academic attainments were found to correlate with the degree of improvements during training ($p < .053$).
(Nelwan et al., 2018)	The highly coached group performed better than the group that received less coaching on visual WM, but not on verbal WM. The highly coached group retained their advantage in mathematics, even though the effect on visual WM decreased.
(Söderqvist et al., 2012)	Training progress predicted improvements on Odd One Out and word span backwards tasks. For Comprehension of Instructions there was a significant training progress observed for female participants only. For Block Design, the authors observed a significant training progress in males which was not observed in females.
(Dahlin, 2011)	The performance on Span board forward, Span board back, and Digit back, and Raven test was improved at Time 2 (T2) relative to T1.
(Dahlin, 2013b)	Mathematical performance improved in the treatment group compared with the control group directly following the five weeks of training (Time 2), but the results of the second post-test (Time 3, approximately seven months later) were no longer significant.
(St Clair-Thompson et al., 2010)	Exploratory factor analysis identified two executive factors: one associated with updating functions and one associated with inhibition. Updating abilities were closely linked with performance on both verbal and visuo-spatial working memory span tasks. Working memory was closely linked with attainment in English and mathematics, and inhibition was associated with achievement in English, mathematics, and science.
(Wiest et al., 2022)	Results showed (1) that attention and WM improved following WM training and (2) that WM training might be related to cognitive structural changes found pre- to post-training among the variables being measured
(Studer-Luethi et al., 2022)	Participants in the WM training group significantly improved their performance from the first two training sessions to the last two sessions in both the farm span task, and the jumping animal task. Participants in the control group significantly improved their response accuracy in the visual-auditory matching task at the first and the last training session.

Effects of working memory training on executive functioning and child ADHD related symptoms (main outcomes)

Table 3. Studies included in the second Research Line

Study	Main Outcomes
(Chacko et al., 2018)	Findings suggest a significant difference in the Dot Matrix task was observed at post behavioral parent training (BPT) assessment, ($d = .71$). Results also indicate significant between-group differences at post-BPT assessment, with WMT (active) + BPT participants scoring higher on Digit and Spatial span, compared to WMT (passive) + BPT participants.

Study	Main Outcomes
(Beck et al., 2010)	Findings suggest an interaction between group and time for parent-rated inattention, such that after treatment the experimental group was rated lower (less inattentive) than the control group on the Conners' Parent Cognitive Problems (d= .79) and on the number of DSM–IV–TR inattention symptom endorsed with a large effect size (d= 1.49).
(Chacko et al., 2014)	A significant main effect of time was observed for parent reported ADHD symptoms domains, with participants across groups showing a diminution in severity over time. However, no analogous findings were observed for teacher rated ADHD inattention or hyperactivity/impulsivity symptoms.
(Green et al., 2012)	The interaction term between group and time was significant, and the difference in improvement between the 2 groups was 12.3 points (±4.6 SE; p =.01). There were no significant training effects on fidgeting, with both groups maintaining the observed pre-intervention levels (.9; ±3.9 SE; p= .81).
(Bigorra, Garolera, Guijarro, & Hervas, 2016)	With respect to EFs scales (BRIEF) as assessed by parents, no significant differences were observed between T0 (*Baseline*) and T1 (1-2 weeks). In contrast, between T1 and T2, the experimental group improved significantly more than the control group according to the WM subscale with a large effect size (d = .86), and this difference was also significant at T2–T0 with a moderate to large effect size (d = .61).
(van Dongen-Boomsma et al., 2014)	In regard to the primary outcome measure (ADHD-RS-I), there were no treatment effects, i.e., any of the ADHD-RS-I subscales. A significant difference in favor of the active group was found on the backward condition of the Digit Span (p = .041). No treatment effect was found on the Digit Span forward condition (p = .980), or any of the other neurocognitive functioning outcomes. Finally, there were no significant differences on the clinical global impressions-improvement scale (p = .514).
(Holmes et al., 2010)	Medication significantly improved composite scores for visuo-spatial WM, but no other aspect of WM; verbal STM, visuo-spatial STM or verbal WM
(Capodieci et al., 2018)	The trained group significantly improved in the Forward Digit Span with a moderate effect size (d = .72). Performance in the Backward Digit Span significantly improved with a high effect size (d= 1.70). On the other hand, ADHD-related symptoms also diminished. For instance, the trained group decreased inattention symptoms in the Early identification of ADHD scale with a moderate effect size (d= .70). This group also decreased hyperactivity symptoms in the same scale with a moderate effect size (d = .66).
(Muris et al., 2018b)	In terms of clinical effectiveness, pharmacotherapy with stimulant medication and the combination treatment produced larger reductions in ADHD symptomatology than Cogmed WMT. Further, results indicated that Cogmed WMT selectively enhanced working memory performance. Finally, after conducting Cogmed WMT, youths and parents were more 'open' to accept pharmacotherapy as intervention, probably because the training increased greater insight in and awareness of the problematic features of ADHD.
(Jones et al., 2020b)	At posttest, the authors found strong evidence of group differences in the nontrained n-back task, as well as substantial evidence for group differences in the measure of inhibitory control. At delayed posttest, the group differences remained, however, the effects were less pronounced than at posttest, and furthermore, they did not survive corrections for multiple comparisons

Effects of working memory training on brain activity in child attention deficit hyperactivity disorder (main outcomes)

Table 4. Studies included in the third Research Line

Study	Main Outcomes
(Hoekzema et al., 2010)	For the task of response inhibition, the authors observed exclusive changes of neural activity in the right inferior frontal cortex, left medial orbitofrontal cortex, left superior frontal cortex, and right middle temporal cortex and main effects contrasts indicate that these changes in neural activity correspond to the results for the main-effects contrast "post-cognitive training > pre-cognitive training".
(Hoekzema et al., 2011)	For the contrast "experimental > control", comparing the volumetric changes after the training period between the groups, selective focal clusters in bilateral middle frontal cortex and right inferior-posterior cerebellum were found. These results indicate a volumetric increase in frontal and cerebellar gray matter in the group subjected to WM training compared with the control group. The contrast "control > experimental" did not yield significant results.
(Stevens et al., 2016)	Changes were almost exclusively activation increases. Normal task-elicited activity increased in inferior frontal sulcus (IFS), caudal Superior frontal sulcus, and medial prefrontal cortex (PFC) during Encoding and Maintenance. Training effects were predominantly, though not entirely, seen in the left hemisphere. In particular, Maintenance activation was greater after WM training in homologous right PFC structures not engaged in these ADHD participants by this task. Left IFS regions showed greater activity regardless of Sternberg task phase, although WM training effects were localized to BA 45 for Encoding and Maintenance, but had a slightly more dorsal peak for Retrieval
(de Oliveira Rosa et al., 2020c)	Findings suggest that there was a group x time x WM-load interaction effect in two clusters in the N-back task, 1) in the right insula and putamen, and 2) in left thalamus and pallidum (p < .001). The interaction reflected decreases in the BOLD signal change from baseline to end- point with increasing WM load in the WM training group, which contrasted with patterns from the non- active group. Besides, the authors reported four clusters of activation in sustained attention task presenting a time x group x ISI (interstimulus interval) interaction, which include: 1) right precuneus, angular gyrus, middle temporal lobe and associative visual cortex; 2) right postcentral and precentral gyrus and right insula; 3) right superior frontal and middle frontal gyrus and 4) left precuneus, associative visual cortex and angular gyrus (p < .001).

Discussion

The aim of this bibliometric analysis was to assess the effect of WM training on symptoms and behaviors of children with ADHD. A point to consider when designing research is whether the study design and outcome measures used actually answer the research question. All studies reviewed in the first research line investigate whether effects from WM Training "transfers" to academic performance in ADHD (Bergman-Nutley & Klingberg, 2014; Dahlin, 2011, 2013b; Nelwan et al., 2018; Nelwan & Kroesbergen, 2016; Söderqvist et al., 2012; Söderqvist & Bergman Nutley, 2015; St Clair-Thompson et al., 2010; Studer-Luethi et al., 2022; Wiest et al., 2022) thus focusing on what has been discussed previously as the *performance* route (Söderqvist & Nutley, 2017).

This implies that WM would act as a bottleneck for pre-existing skills and that increasing its capacity would unlock previously constrained academic potential. Such effects would be apparent only on academic tasks with a WM load close to each subject's limits. Due to the complexity of both reading and mathematical learning it is also not obvious that improving WM will lead to linearly associated improvements in the academic skills measured. Two alternatives have been proposed, one in which a minimum level of capacity is required for simple mathematics or reading skills, such as for example identifying letters or reading and understanding a short and simple sentence. In this case, having a WM above this threshold might not provide additional benefits on such tasks. On the other hand, more advanced reading tasks such as reading and understanding a whole paragraph of more complicated text might benefit from a higher WM independently of the baseline, thus exhibiting a linear pattern of improvement with an increased WM. Similarly, to what have been previously argued, the complexity of the relation between WM and academic performance urges for task content analyses of outcome measures if we are to better understand when, how and for whom WM training leads to significant transfer effects (Raghubar et al., 2010).

Although learning itself takes time to manifest, there are other ways to study the process of learning as was done in a randomized, controlled study of children with ADHD (Green et al., 2012). After WM Training, children in the intervention group were observed to have fewer occurrences of looking away and playing with objects during an academic task compared with the children in the control group, concluding that WM training had indirect impact on academic learning. Another study explicitly set out to assess both hypothetical routes of impact with assessments directly after training as well as after 12 months (Dunning et al., 2013). Other studies have investigated the *learning* route (Holmes & Gathercole, 2014; Söderqvist & Bergman Nutley, 2015) only, that is, that WM Training would positively influence the learning capacity of the participants. This hypothesis can be simplified as: WM Training + education > education alone.

Within this premise, care must be taken in selecting outcome measures that match the content of the education part of the equation. For example, in ADHD children, only specific instruction and practice will enable that child to solve a problem using Pythagoras theorem (an example from the WIAT-II numerical operations subtask). Most of the studies discussed in this review have used short standardized assessments such as the WRAML-2, and results from these have been used to generalize conclusions to the much wider term "academic achievement." Although these are good measures for their own purpose, such as identifying individuals with specific learning difficulties, it is important to keep in mind that they only provide a snapshot of a student's academic abilities. It is therefore surprising that most studies using these have not included a discussion on how the particular tasks included (a) relate to WM and (b) for math primarily, match the curriculum to reflect what the students have been learning in school since the completion of training.

One approach that is more likely to capture progress on curricular content is to use metrics that schools already use, such as exams and national achievement measures, since these are specifically designed to capture learning progress. So far there have been two studies implementing WM Training in a school environment that have also used outcome measures based on assessments that the schools choose themselves as part of their typical academic assessment (Holmes & Gathercole, 2014; Söderqvist & Bergman Nutley, 2015). Both these studies stand out as finding significant improvements on mathematics and reading performance at long-term follow-up. It should however be noted that while year 6 ADHD students in the Holmes and Gathercole study demonstrated significant increases in both mathematics and English, the effects for year 5 students were less clear.

Using established school metrics also has the benefit of the assessments being salient to the students since these contribute to grades and/or are presented in the usual educational context. Students might therefore be more motivated when performing these tests compared to tests performed for a research study only. Another potential benefit is reducing the risk of Pygmalion effect driving the results where high expectations lead to improved performance. Although these studies have employed no-contact control conditions, placebo effects are unlikely to explain the results when using regular school-based assessments administered by the teachers, about 10–24 months after the training, and with no obvious link to the study (Holmes & Gathercole, 2014; Söderqvist & Bergman Nutley, 2015).

Regarding the second research line, the reviewed studies show a clear structure of cognitive abilities in which the constructs of WM, attention, and inhibition are distinct but related cognitive constructs (Chacko et al., 2014, 2018). In line with previous research (Schmank et al., 2019), findings show a cohesive structure between WM, attention, and inhibition. This corroborates decades of research on the executive attention theory of WM (Engle, 2002) that postulates that attention is a central component to variation in WM abilities.

Generally, children's performance improved significantly not only in basic processing speed (Stroop task, Part 1 of TMT) but also on the higher level of the cognitive function such as interference inhibition (Part 3 and 4 of Stroop), and efficient shifting (Part 2 of TMT). Taken together, these findings showed that WM training improved most components of Executive Functions as demonstrated by the significant improvements on performance during other neuropsychological tests. This is in line with former studies because the EF capacity and its associated levels of brain activity are not static but may be altered by task-repetition or training (Capodieci et al., 2018). In fact, WM training might improve cognitive function by increasing activation of the frontal lobe (Bigorra, Garolera, Guijarro, & Hervas, 2016) which is crucial for EF.

In this review, The EF improvements not only showed in the laboratory tests but also showed in the child's everyday life captured by BRIEF. These indicated that a wide variety of EF skills were improved in child's real daily life, which were very important since the everyday EF problems were predictors of comorbid psychopathology (Beck et al., 2010; Bigorra, et al., 2016; Muris et al., 2018a; van Dongen-Boomsma et al., 2014). In addition to EF improvements on neuropsychological tests and daily life, the child's ADHD symptoms and behaviors also showed significant improvements. This was in line with a study using meta-cognitive therapy, which targeted EF impairments and developed self-management skills showed marked improvement with respect to adult's ADHD symptoms (Solanto et al., 2008). Therefore, WM training programs should tailor to meet child's real-world situations or settings (Smith et al., 2020). The parent involvement might also contribute these improvements because parenting interventions were beneficial for ADHD symptom reduction and neuropsychological function (Tarver et al., 2015).

Finally, in regard to the third research line, this review has demonstrated that brain imaging studies of WM training in ADHD report significant neural effects often independently of behavioral changes in frontoparietal and front striatal circuitry (Hoekzema et al., 2010, 2011). This review also showed that there is a paucity of far-transfer measures of impulse control in neuroimaging studies of WM training, despite a wealth of evidence emphasizing that frontoparietal and striatal circuits not only contribute to changes in WM function across the lifespan but are also associated with the cognitive control of impulsivity (de Oliveira-Rosa et al., 2020b; Stevens et al., 2016).

As such, studies examining the neural effects of WM Training associated with impulse control could be a fruitful research avenue to pursue for those aiming to improve neural processes in people with ADHD (de Oliveira-Rosa et al., 2020b), which often demonstrate comorbid impulse control deficits (Chacko et al., 2018). This review also highlighted that the majority of brain imaging studies of WM Training have relied on functional magnetic resonance imaging or fMRI—including task-based, resting state and functional connectivity analyses. Other imaging studies have utilized structural measures, including MRI, voxel-based morphometry for volumetric analyses, shape and cortical thickness measures, and examination of myelination neuroplasticity changes in the "connectome" after WM Training.

In addition, another study explored the utility of brain stimulation measures (e.g., transcranial direct current stimulation [tDCS] and transcranial magnetic stimulation [TMS]) as an adjunct to improve WM Training far-transfer effects that may translate into long-term behavioral changes (Brooks et al., 2020). Finally, the four studies in this research line have highlighted three debates within the WMT neuroimaging field in ADHD: a) the pattern of brain activation underlying far-transfer, b) whether WMT is associated with increased or decreased neural activation, and c) whether there are differential neural changes with WMT in younger versus older ADHD participants.

Disclosure and conflict of interest

The authors declare that this research was conducted in the absence of any potential conflict of interest.

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