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Efficacy of cognitive training on executive functions in healthy older adults: a systematic review with meta-analysis of randomized controlled trials

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ABSTRACT

Objective: Systematically review randomized controlled trials on the efficacy of cognitive training on executive functions in healthy older people.

Measures: The outcome measures were related to inhibitory control, working memory, and cognitive flexibility.

Results: Thirty-one trials were included in the systematic review and thirteen trials in the meta-analysis. In the overall analysis, the cognitive training enhanced inhibitory control when measured by the Stroop task ($p < .001$, $d = 1.64$) and working memory when measured by the Corsi Block task ($p = .002$, $d = .16$). A marginal significance was found for working memory in the Digit Span task – Forward ($p = .06$, $d = .92$). However, cognitive training did not enhance inhibitory control when measured by the Go/No-Go task ($p = .76$, $d = .59$), working memory when measured by the Digit Span – Backward ($p = .72$, $d = .95$) and N-Back ($p = .10$, $d = .26$) tasks, and cognitive flexibility when measured by Trail Making – Part B ($p = .08$, $d = .27$) and Semantic Fluency ($p = .49$, $d = .06$) tasks.

Conclusion: Mixed evidence was found for inhibitory control and working memory; cognitive flexibility showed no evidence of improvement.

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KEYWORDS
Older adults; meta-analysis; cognitive aging; cognitive training; executive functions

The increase in human longevity, driven by improvements in living conditions, nutrition, medical technology, and cognitive development, has dramatically changed the prospects of future life, especially for older adults (Caswell & Zarulli, 2018; Maldonado Briegas et al., 2020). The increase of longevity must be seen as a modern science achievement. The United Nations estimates that the number of older adults (i.e. ≥ 65 years old) worldwide will rise from 0.7 billion (9%) in 2019 to 1.5 billion (16%) in 2050 (United Nations, 2019). However, a higher proportion of older people are susceptible to illnesses since the aging process is generally described as being closely associated with the onset of many diseases (Lazarus & Harridge, 2018). The review

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proposed by Jaul and Barron (2017) summarized the main age-related diseases in older adults and highlighted mild short-term memory loss, word-finding difficulty, and slower processing speed as normal parts of aging. The neuropsychological literature indicates that healthy older adults showed worse performance than healthy younger adults on a variety of cognitive tasks that assessed: processing speed, inhibition, and visual-spatial ability (Ferguson et al., 2021; Kujawski et al., 2021; Langeard et al., 2021; Li et al., 2021). In contrast, the review proposed by Harada et al. (2013) reported that some crystallized abilities (e.g. vocabulary) show a slower decline due to brain aging and may even improve with age because of knowledge accumulated during their lives. For instance, older adults show better performance when compared to younger adults on tasks in which they use wisdom (e.g. judgment and problem-solving tasks; Dumas, 2017). Therefore, there is a great and growing effort of the neuroscience community on the nature of later life, including how to sustain cognitive health and even how to enhance it (Foster & Walker, 2021).

Cognitive functions (e.g. perception, attention, memory, problem solving, executive functions, decision making, intelligence) play a crucial role in our functioning, impacting our everyday life activities (see Demir Akça et al., 2014; Murman, 2015). Some functions—especially the executive functions—decline gradually over time as a result of the continuous aging process, that is, nonpathological and age-associated cognitive decline (Murman, 2015). The executive functions are key functions for everyday life, allowing individuals to plan ahead, focus their attention, switch between different tasks, and maintain effective levels of independent functioning (Corbo & Casagrande, 2022; Ferguson et al., 2021). The literature shows that a good performance in executive functions is associated with successful goal attainment in a variety of contexts (e.g. Pascual et al., 2019; Peng et al., 2022), independence, autonomy, and quality of life (Coppin et al., 2006; Gamage et al., 2018), as well as oriented behaviours and complex situations, such as crossing the street (Nicholls et al., 2022). Deficits in executive functions have been associated with poor outcomes, such as poor social function, impaired instrumental activities of daily living, and depression (Alexopoulos et al., 2000; Duggan et al., 2017). Studies conducted with older adults have demonstrated declines in executive cognitive functions (e.g. inhibition control, mental shifting; Peng et al., 2022) which is gradually mediated by a decrease in brain volume (in the right parietal and prefrontal cortices, for instance; Fastame et al., 2022). As a result of aging, the executive functions are one of the first cognitive functions to decline due to micro and macrostructural alterations in the brain connectivity (for a functional and structural perspective, see Fjell et al., 2017). The executive functioning is a higher-order processing activity in the brain, and it is the process by which individuals exercise conscious control over their thoughts and actions (Fan & Wang, 2023). Most related changes in executive functions are suggestive of impairment in the frontal lobes, and changes in the frontostriatal circuit (i.e. neural pathways connecting the frontal lobe with the basal ganglia) are possibly the most significant cause of impaired executive function in older adults with no dementia (Lima-Silva et al., 2012).

In terms of constituents of executive functioning, one of the most accepted theoretical frameworks proposes a core triad of functions: inhibitory control, working memory, and cognitive flexibility (see Diamond, 2013; Lehto et al., 2003; Miyake et al., 2000). Inhibitory control is the cognitive ability to suppress or countermand a thought,

action, or feeling (Spechler et al., 2016). It allows an individual to inhibit their impulses and natural, habitual, or dominant behavioural responses to stimuli in order to select more appropriate behaviours consistent with one's goals (Li et al., 2022). Inhibitory control can be measured using classical paradigms of experimental psychology, for example, the Stroop task, Go/No-Go task, and the Stop-Signal task (Kang et al., 2021). Working memory is the cognitive ability that allows an individual to hold a small amount of information that can be held in mind and applied in the execution of cognitive tasks (Cowan, 2014). It is essential to all advanced thinking to learn facts or skills (Bergman Nutley & Söderqvist, 2017). Experimentally, working memory can be measured using classical paradigms, for example, the Digit Span task, Letter/Number Sequencing task, and the Corsi Block task (Shelton et al., 2009). Cognitive flexibility is the ability that allows an individual to efficiently adjust one's behaviour according to a changing environment (Dajani & Uddin, 2015). It enables individuals to integrate external evidence into previous expectancies (Romero-Ferreiro et al., 2022). Experimentally, cognitive flexibility can be measured using classical paradigms, for example, the Trail-Making Task—Part B, Wisconsin Card Sorting Task, and Fluency tasks (Takeda & Fukuzaki, 2021).

The human brain is inherently plastic and is continually adapting to its environment. Thus, despite the inevitable aging process, engagement in cognitive activities (e.g. learning a new language, maintaining social connections, and engaging in challenging cognitive tasks) can potentially mitigate cognitive declines (Stieger & Lachman, 2021). Importantly, cognitive training of executive functions seems to increase functional and neural plasticity, even in older age (Nguyen et al., 2019). Cognitive training is an intervention centred on the cognitive performance that uses a set of standardized behavioural task protocols that tackle cognitive functions (Golino & Flores-Mendoza, 2016), and that may be associated with other interventions (e.g. physical exercise; Anguera et al., 2022). These 'trainable' functions range from lower level processes—for example, perception: biological motion—to higher order processes—for example, executive functions: working memory (see Legault & Faubert, 2012; Weng et al., 2019). The efficacy is usually assessed through cognitive evaluation (e.g. neuropsychological testing) for one or several cognitive domains before and after the intervention.

Considering that older adults have a high risk of serious cognitive diseases, identification of strategies and possible interventions for preventing cognitive decline is necessary (Giuli et al., 2016). In recent times, several devices and platforms have started to play a significant role in cognitive training since such training can potentially be undertaken at any time and accessed from anywhere (Klimova, 2016). Rapid advances in computing technology had evolved exponentially over time due to a fusion of technologies that are blurring the lines between physical, digital, and biological spheres (Park, 2016). As a result, this has enabled researchers and clinical professionals to conduct accessible and fine-tuned cognitive training using virtual reality, interactive video game playing, mobile setup, and other cutting-edge technologies (Ge et al., 2018).

Over the last years, many studies showed positive results of cognitive training on cognitive functioning in older adults. A review proposed by Sanjuán et al. (2020) endorsed the effectiveness of cognitive interventions in older adults. However, the authors highlighted aspects that must be met by proper experimental protocols for

cognitive training (e.g. session length, total number of sessions, measures of daily functioning) in order to make the intervention more effective. Additionally, with the growing number of publications related to cognitive training applied in clinical populations, there has been an increase in the number of systematic reviews with and without meta-analysis. A meta-analysis proposed by Yun and Ryu (2022) demonstrated cognitive training was the most effective intervention in healthy older adults in comparison to cognitive stimulation (e.g. reality orientation) and cognitive rehabilitation (e.g. activities to improve the performance of daily activities). Nevertheless, systematic reviews show conflicting results (Makin, 2016; Traut et al., 2021). Some reviews fond clear benefits to a trained ability—for example, executive function in older adults with cognitive impairment (see Abd-alrazaq et al., 2022), while other reviews yield little to no evidence of benefit from cognitive training (see Sala et al., 2019). In addition, the reviews usually assess the efficacy of cognitive training on outcomes related to global cognition and neglect cognitive subdomains.

Therefore, and because cognitive training deals extensively with several areas (e.g. basic science, health, public policies, industry, and marketing), systematic reviews must be conducted periodically to present the state-of-the-art of the field and show its improvements in terms of methodological control. Four previous studies have performed systematic reviews with meta-analysis to address the effect of cognitive training on executive function in healthy older adults (Chiu et al., 2017; Lampit et al., 2014; Nguyen et al., 2019; Wollesen et al., 2020). Considering the high heterogeneity of the trials in terms of intervention implemented, type of controls, cognitive processes assessed, and response variables, in addition to the increase in published papers, professionals and decision makers are seeking reviews with detailed data and higher degrees of specificity. The meta-analyses conducted by Lampit et al. (2014) and Chiu et al. (2017) investigated outcomes related to different cognitive functions (memory, attention, processing speed, executive function, and visual-spatial skills) in healthy older adults. Nguyen et al. (2019) segmented the meta-analysis by executive functions subdomains (inhibitory control, working memory, and cognitive flexibility), and Wollesen et al. (2020) split the meta-analysis by type of control (active or passive) in the same population. We went further and ran task-specific meta-analyses and provided meta-analytic data of the neuropsychological tests/paradigms most used in cognitive training protocols for older people.

Method

The current study was registered in PROSPERO (ID: CRD42021237057) and conducted in accordance with recommendations outlined by the PRISMA group guidelines (Page et al., 2021; see Supplementary Material—Appendix A for PRISMA-checklist).

Eligibility criteria

We targeted the research question using the PICOS framework: Population—cognitively healthy older adults; Intervention—cognitive training to enhance or maintain executive functioning; Comparison—active or passive control groups; Outcome

–neuropsychological measures of executive functions; Study design—randomized controlled trials.

Type of studies

We first identified and then collected peer-reviewed scientific papers of trials from online electronic databases written in any language that investigated the effect of cognitive training on executive functions outcomes in cognitively healthy older adults.

Type of participants

The total experimental sample of each trial had to comprise individuals aged 59 years and older with normal cognitive functioning, and that have not been diagnosed with mild cognitive impairment or any form of dementia (experimental and control groups). The eligibility was confirmed by examining the baseline characteristics of the sample and the trial inclusion criteria.

Type of intervention

The intervention consisted of cognitive training alone or combined with other interventions (e.g. physical exercise, neuromodulation). We considered cognitive training as an approach that involves a set of standardized tasks designed to maintain or enhance cognitive processes (Simons et al., 2016). Interventions that significantly differ from cognitive training (i.e. not following a series of regular mental activities designed to maintain or improve cognitive performance), such as cognitive behavioural therapy and mindfulness, were excluded.

Type of outcome measures

The outcome included performance on at least one cognitive test administered both before (baseline) and after the cognitive training program. We consider both standardized instruments and paradigm-based experimental tasks as cognitive tests. Performance improvement was expected in executive functions in neuropsychological tests when comparing baseline pre-training and immediate post-training. In order to employ same-construct comparisons, we categorized the outcome measures by distinct executive functions constituents: inhibitory control, working memory, and cognitive flexibility.

Information source

The following online databases were searched up to April 2021 to identify relevant trials: MEDLINE (PubMed), PsycINFO, The Cochrane Library Cochrane Central Register of Controlled Trials (CENTRAL), Web of Science (Science and Social Science Citation Index), and SciELO (Scientific Electronic Library Online). For the identification and use of descriptors (i.e. specific keywords), we resorted to medical subject headings (MeSH) terms. To include as many trials as possible in addition to the MeSH terms, we included additional descriptors with terms not directly linked to MeSH (called 'Text word'), but closely related to the investigated research topic. Subsequently, a new search was

performed in additional directories up to April 2022 to identify possible updates to previously obtained trials: Epistemonikos (www.epistemonikos.org), Lens (www.lens.org), and Cognitive Training Data (www.cognitivetrainingdata.org). To elaborate the search strategy in the first two directories, we used the 2D Search open-source software (www.2dsearch.com), in which queries are formulated by manipulating objects on a two-dimensional canvas. In the Cognitive Training Data directory, we extracted the trials using Mendeley Reference Manager version 2.63 open-source software (www.mendeley.com). See Supplementary Material—Appendix B for the detailed search strategy for both searches.

Study selection and risk of bias

There were no restrictions on language and publication date. Two authors (RLO and SRF) independently removed the duplicate items and performed the initial screening (i.e. titles and abstracts reading) of studies identified by the specific search strategy. Divergence in study selection was resolved by the third author (RMJ). The two authors (RLO and SRF) subsequently read the selected studies' full text for potentially eligible studies. We utilized the Rayyan open-source free web-tool software (rayyan.qcri.org) during the entire screening process (on the advantages of Rayyan, see Ouzzani et al., 2016). The two authors (RLO and SRF) collected data about trial identification (title, authors, and year of publication), sample characteristics (sample size, mean age, standard deviation of each group), characteristics of the cognitive training, its duration (sessions), type of control group involved (active or passive), and the outcome measures (inhibitory control, working memory, and cognitive flexibility).

One author (RLO) assessed the methodological quality of the included trials in meta-analysis using the Cochrane Risk of Bias 2 tool (RoB2; for a description, see Sterne et al., 2019). This tool provides a framework for assessing the risk of bias in a single estimate of an intervention effect reported from a trial. RoB2 is structured into seven bias domains (i.e. random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other bias).

Data extraction and analysis

For the systematic review, the following data were extracted: first author and year, sample, mean age, cognitive training type, dose, sessions, length, sessions per week, executive function outcomes, and control groups. For the meta-analysis, the continuous data to perform the meta-analysis was extracted by one reviewer (RLO) and checked by a second reviewer (RMJ). To perform the meta-analysis, we adopted the Review Manager version 5.4 open-source software (for a description, see Cochrane, 2022). The main outcome was the standardised mean difference (SMD) from pre- to post-training in the experimental group(s) (i.e. cognitive training) and control group(s) (i.e. active or passive).

The analyses on the SMD were conducted for each of the executive function subdomains. Precision of the SMD was calculated for each trial by 95% confidence intervals (CI). The trials were required to have measured participants baseline ability in the

trained cognitive skill, and this measure could come from the same task that was later used for training or from a different task that assessed the same cognitive skill. Furthermore, trials were required to have measured participants cognitive training outcomes using gain scores. The continuous data values were entered into a spreadsheet (available at https://osf.io/64xmj/), and then organized to run the meta-analysis.

The selected trials were inserted in a separate spreadsheet tab containing data referring to the pre- and post-intervention, including the sample, mean difference, and standard deviation of the experimental and control groups. Considering that the included trials had distinct populations, intervention parameters, and settings, a random effect model was employed in the meta-analysis. The heterogeneity was assessed by the I^2 statistic and 95% CI. The following I^2 statistics were considered: 0–40%: not important/low heterogeneity; 30%–60%: moderate heterogeneity; 50%–90%: substantial heterogeneity; 75%–100%: considerable heterogeneity (Deeks & Higgins, 2022). The I^2 statistic reports the percentage of variation across selected studies that is due to heterogeneity among studies (from a statistical origin) rather than chance. The higher the I^2, the higher the likelihood of drawing incorrect metanalytic inferences on the clinical relevance, that is, the effect of the cognitive training (see Melsen et al., 2014). As a complementary measure of heterogeneity, we also calculated the Tau-squared, which measures variance of the true effect sizes. Assessment of clinical relevance was made using three categories: small effect (mean differences [MD] < 10% of the scale; standardised mean difference [SMD] < 0.5); medium effect (MD from 10% to 20% of the scale; SMD from 0.5 to 0.8); large effect (MD > 20% of the scale; SMD > 0.8) (Furlan et al., 2009). In addition, the effect size was assessed by the Cohen's d. Heterogeneity and clinical relevance assessments together allow inferences on the intervention efficacy and enable professionals to decide about the applicability of the results to their target population. A funnel plot for identifying possible publication bias was calculated, and a sensitivity analysis was planned to identify if a specific trial changes the overall effect, by repeating the meta-analysis with one trial omitted at a time (forest plot inspection for outliers). We adopted a significance level of 5% for all tests.

Results

Study selection

The initial search in the electronic databases yielded 3,544 trials. After removal of duplicates 2,587 trials were screened. After abstract and title screening, we assessed 75 full-texts for eligibility. We subsequently included 31 trials in the systematic review and 13 trials were selected for meta-analysis. The PRISMA-based flow diagram provides an overview of the trials' selection process (Figure 1).

Characteristics of the included studies

The characteristics of the individual trials are summarized in Table 1. The publication year of the selected trials ranged from 2009 to 2022, and the participants' age ranged between 59 and 82 years old. The included trials had a total of 2,783 participants of

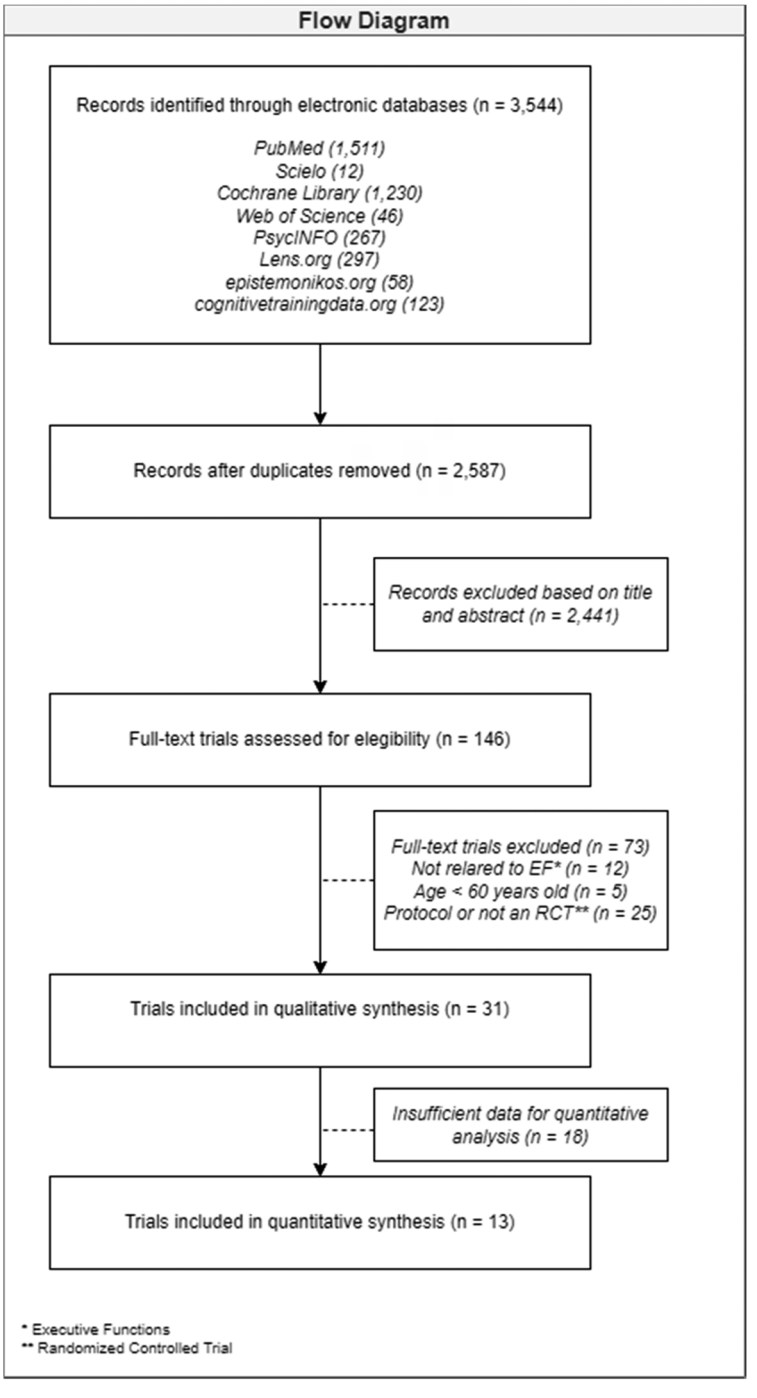

Figure 1. Flow diagram with data related to trials screening throughout the whole process.

both sexes. The studies extracted from the systematic review had an average (mean ± standard deviation) of 23.63 ± 15.69 total training hours; 31.10 ± 19.06 total training sessions; 3.16 ± 1.42 sessions per week; and 50.63 ± 28.38 min per session. Regarding the type of

Table 1. The characteristics of individual trials.

Authors	Year	N	Mean age	CT*	[1]	[2]	[3]	[4]	IC	WM	CF	AC	PA
Nouchi et al.	2019	EG: 30 CG: 30	EG: 71.67 ± 3.62 CG: 73.11 ± 3.90	TV	10.00	30	20.00	5	✓	✓		✓	
Schoene et al.	2015	EG: 47 CG: 43	EG: 82.00 ± 7.00 CG: 81.00 ± 7.00	VG	21.95	31	27.40	3	✓	✓	✓		✓
Ballesteros et al.	2014	EG:17 CG:13	EG: 68.80 ± 5.15 CG: 69.20 ± 5.91	CP	20.00	20	60.00	2		✓	✓		✓
Shatil et al.	2014	EG: 60 CG: 59	EG: 67.70 ± 5.80 CG: 68.30 ± 5.80	TV	8.00	24	20.00	3		✓	✓	✓	
Reve and Bruin	2014	EG: 76 CG: 69	EG: 81.90 ± 6.30 CG: 81.10 ± 8.30	CP	6.00	36	10.00	3			✓	✓	
Peretz et al.	2011	EG: 66 CG: 55	EG: 68.6 ± 7.70 CG: 66.9 ± 7.30	CP	18.00	36	30.00	3		✓	✓	✓	
Adcock et al.	2020	EG: 15 CG: 16	EG: 77.00 ± 6.40 CG: 70.90 ± 5.00	VG	32.00	48	40.00	3	✓	✓	✓		✓
Simon et al.	2018	EG: 41 CG: 41	EG: 72.40 ± 5.60 CG: 73.70 ± 6.50	CP	16.67	25	40.00	5		✓	✓	✓	
Hardcastle et al.	2022	EG: 30 CG: 28	EG: 70.67 ± 3.99 EC: 71.11 ± 5.28	CP	40.00	60	40.00	5	✓	✓			✓
Nouchi et al.	2012	EG: 14 CG: 14	EG: 68.86 ± 2.07 CG: 69.31 ± 2.82	CP, VG	5.00	20	15.00	5		✓	✓	✓	
Turner et al.	2019	EG: 15 CG: 15	EG: 67.00 ± 5.87 CG: 68.08 ± 4.54	CP	20.00	10	120.00	2	✓	✓	✓	✓	
Grönholm-Nyman et al.	2017	EG: 17 CG: 16	TG: 68.76 ± 6.68 CG: 68.31 ± 8.28	CP	15.00	15	60.00	3	✓	✓	✓	✓	
Kazazi et al.	2021	EG: 26 CG: 26	EG: 65.42 ± 5.40 CG: 64.38 ± 5.00	CP	9.00	12	45.00	2	✓	✓	✓		✓
Basak et al.	2008	EG: 19 CG: 20	EG: 70.05 ± 4.94 CG: 69.10 ± 6.06	VG	23.5	15	90.00	3	✓	✓	✓		✓
Estrada-Plana et al.	2021	EG: 12 CG: 15	EG: 81.83 ± 8.86 CG: 82.93 ± 8.95	VG	10.00	5	60.00	2	✓	✓		✓	
Lee et al.	2020	EG: 29 CG:39	EG: 70.41 ± 3.56 CG: 69.69 ± 3.88	CP	35.00	50	42.00	5	✓	✓	✓	✓	
Jaeggi et al.	2020	EG: 78 CG: 77	EG: 72.33 ± 5.51 CG: 73.39 ± 5.33	CP	6.67	20	20.00	2	✓	✓			✓
Falbo et at.	2016	EG: 20 CG: 16	EG: 71.50 ± 6.70 CG: 73.70 ± 4.50	EC	24.00	24	60.00	2	✓	✓		✓	
Mozolic et al.	2011	EG: 33 CG: 33	EG: 69.40 ± 3.20 CG: 69.40 ± 2.50	CP	8.00	8	60.00	1	✓	✓	✓		✓
Smith et al.	2009	EG: 242 CG: 245	EG: 75.60 ± 6.60 CG: 75.00 ± 6.30	CP	40.00	40	60.00	5		✓		✓	
Perrot et al.	2019	EG1:12 EG2:12 CG: 11	EG1: 63.75 ± 2.49 EG2: 64.67 ± 3.17 CG: 65.55 ± 2.91	VG	24.00	24	60.00	3	✓	✓	✓		✓
Eggenberger et al.	2015	EG1:24 EG2:22 CG: 25	EG1: 77.30 ± 6.30 EG2: 78.50 ± 5.10 CG: 80.80 ± 4.70	CP, VG	34.67	52	40.00	2		✓	✓	✓	
Gajewski et al.	2020	EG: 32 CG1: 33 CG2:37	EG: 71.00 ± 4.20 CG1: 71.00 ± 4.50 CG2: 70.00 ± 4.20	CP, PP	49.07	32	90.00	2	✓		✓	✓	
Weicker et al.	2018	EG1: 20 CG1:20 CG2:20	EG1: 67.80 ± 3.90 EG2: 67.70 ± 3.10 CG: 67.50 ± 5.70	CP	9.00	12	45.00	3	✓	✓	✓	✓	✓
Ten Brinke et al.	2019	EG1: 39 EG2: 38 CG: 40	EG: 71.36 ± 5.14 EG2: 72.88 ± 5.17 CG: 72.46 ± 4.11	CP	24	24	60.00	3	✓		✓	✓	
Meltzer et al.	2021	EG1: 28 EG2: 24 CG: 24	EG1: 69.57 ± 2.97 EG2: 70.08 ± 2.89 EG3: 70.00 ± 2.62	SP	40	80	30.00	5	✓	✓			✓
Nouchi et al.	2021	EG1:36 EG2: 36 CG1: 34 CG2: 36	EG1: 67.97 ± 3.12 EG2: 67.42 ± 4.78 CG1: 67.59 ± 4.58 CG2: 67.86 ± 4.92	CP	21.00	84	15.00	7	✓	✓		✓	
Shatil	2013	EG1: 33 EG2: 29 TG3: 29 CG: 29	EG1: 80.00 ± 5.43 EG2: 79.00 ± 5.49 EG3: 81.00 ± 5.25 CG: 79.00 ± 5.76	CP	32.00	48	40.00	3	✓	✓	✓	✓	
Gajewski and Falkenstein	2018	EG1: 35 EG2: 32 EG3: 34 CG: 40	EG1: 71.90 ± 7.40 EG2: 70.90 ± 4.10 EG3: 71.10 ± 4.50 CG: 69.90 ± 4.20	CP, PP	48.00	32	90.00	2		✓		✓	✓
Desjardins-Crépeau et al.	2016	EG1: 22 EG2: 20 CG1: 16 CG2: 18	EG1: 72.70 ± 7.40 EG2: 73.20 ± 6.30 CG1: 70.90 ± 7.40 CG2: 72.5 ± 7.00	CP	72.00	36	120.00	3	✓		✓	✓	
Chen et al.	2017	EG1: 19 EG2: 17 EG3: 15 EG4: 15 CG: 20	General: 68.55 ± 5.74	EC	10.00	10	60.00	1		✓			✓

Notes. *Type of cognitive training (CT) based on the modality of intervention, [1] Total number of training hours, [2] Total number of CT sessions, [3] Single session length in minutes, [4] Number of sessions per week. Acronyms: Experimental Group (EG), Control Group (CG), TV: TV-Based (stimuli and task delivered on a television with no behavioural responses registered by any TV system), VG: Video Game-Based (stimuli and task adapted to a video game interface with manual motor responses using joysticks and registered by a video game system), CP: Computer-Based (stimuli and task in computational interface), PP: Paper-and-pencil-based (analogic stimuli), EC: Ecological Training (tasks in rich and real-world environments related to daily activities), SP: Smartphone App Training (computational stimuli and task adapted to smartphones interface), IC: Inhibitory Control, WM: Working Memory, CF: Cognitive Flexibility (IC, WM, and CF columns indicate whether this mental functions were investigated), AC: Active, PA: Passive.

cognitive training, the selected trials presented approaches based on computer ($n = 20$), videogame ($n = 7$), TV ($n = 2$), paper-and-pencil ($n = 1$), ecological ($n = 1$), and smartphone app ($n = 1$). A total of 21 trials reported an outcome related to inhibitory control, 27 trials related to working memory, and 21 trials related to cognitive flexibility as reported by the columns IC, WM, and CF in Table 1, respectively. Regarding the control groups, 20 trials reported active control group(s) and 13 trials reported passive control group(s)[1].

The trials were conducted in the United States of America (Basak et al., 2008; Hardcastle et al., 2022; Jaeggi et al., 2020; Lee et al., 2020; Mozolic et al., 2011; Shatil, 2013; Simon et al., 2018; Smith et al., 2009; Turner et al., 2020), Canada (Desjardins et al., 2016; Meltzer et al., 2023; Ten Brinke et al., 2020), Japan (Nouchi et al., 2012, 2019, 2021), Australia (Schoene et al., 2015), Spain (Ballesteros et al., 2014; Estrada-Plana et al., 2021), Switzerland (Adcock et al., 2019; Eggenberger et al., 2015; Van Het Reve & De Bruin, 2014), Israel (Peretz et al., 2011), Germany (Gajewski et al., 2018, 2020; Van Het Reve & De Bruin, 2014; Weicker et al., 2018), France (Perrot et al., 2019), Finland (Grönholm-Nyman et al., 2017), Iran (Kazazi et al., 2021), Italy (Falbo et al., 2016), Sweden (Simon et al., 2018), China (Chiu et al., 2017) and multi-countries (Shatil et al., 2014). The location where the study was carried out (registration in the ethics committee) and location of the first author's affiliation were taken as criteria to establish the study origin.

Meta-analyses

Here we present the meta-analyses of each executive function subdomain according to a core triad of functions. Only trials that reported pre- and post-intervention data were included (i.e. MD and standard deviation). Based on the available data for the meta-analysis, we presented the results for the most frequent tasks conducted: Stroop and Go/No-Go tasks for inhibitory control; Digit Span (Forward and Backward), N-Back, and Corsi Blocks tasks for working memory; and Semantic Fluency and Trail Making—Part B tasks for cognitive flexibility.[2]

Effects on inhibitory control

The effects of cognitive training on inhibitory control were evaluated in four trials (Kazazi et al., 2021; Nouchi et al., 2019; Perrot et al., 2019; Weicker et al., 2018), which were measured by the Stroop and Go/No-Go tasks. The meta-analysis on inhibitory control measured by the Stroop task resulted in a statistical significance (overall effect) in favour of cognitive training intervention when compared to active/passive controls (Figure 2 upper half; $n = 143$ participants, $SMD = .78$, CI [.33, 1.22], $p < .001$, $d = 1.64$). There was low heterogeneity in the overall analysis ($I^2 = 35\%$, $Tau^2 = .05$). Additionally, the meta-analysis resulted in a statistical significance (subgroup effect) in favour of cognitive training when compared to the active control ($n = 120$ participants, $SMD = .61$, CI [.25, .98], $p = .001$, $d = 6.41$, $I^2 = 0\%$, $Tau^2 = .00$) and passive control ($n = 23$ participants, $SMD = 1.53$, CI [.58, 2.48], $p = .002$, $d = .41$).

The meta-analysis on inhibitory control measured by the Go/No-Go task did not show statistical significance (overall effect) in favour of cognitive training intervention when compared to active/passive controls (Figure 2 bottom half; $n = 92$, $SMD = -0.24$,

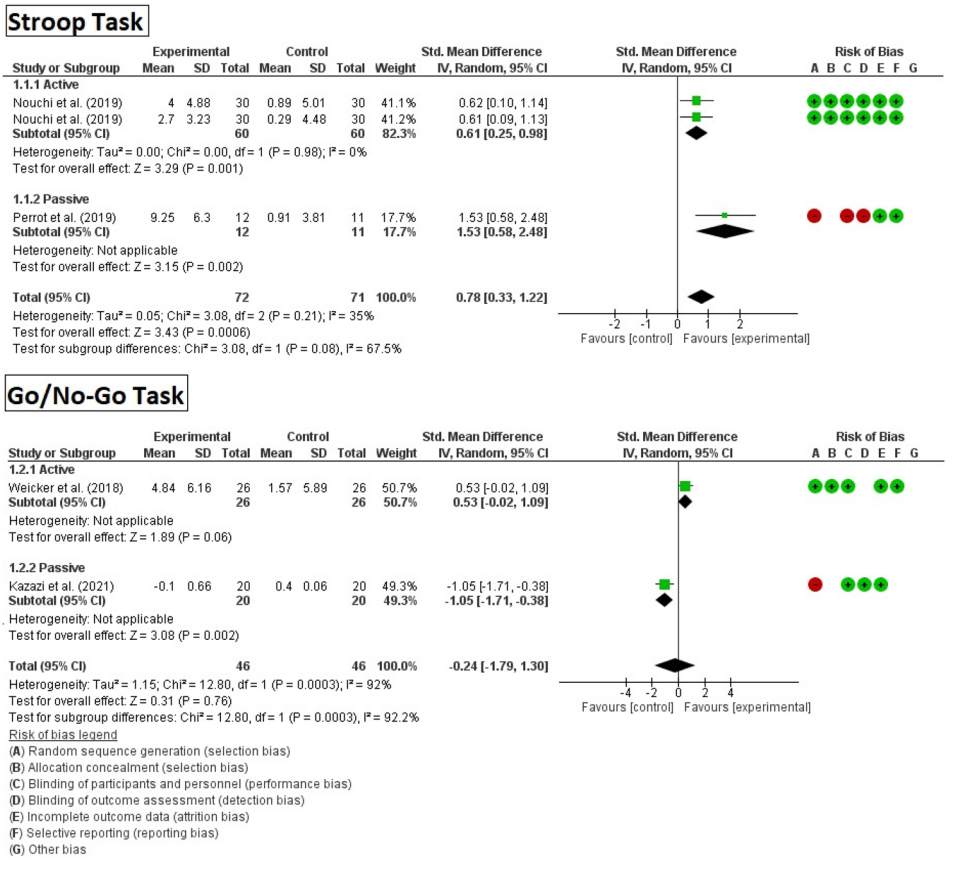

Figure 2. Inhibitory control measured by the Stroop task and Go/No-Go task.
Notes. Standardised mean difference effects of cognitive training compared with active/passive controls on inhibitory control outcomes in healthy older adults measured by the Stroop task (hits in the incongruent condition) and Go/No-Go task (hits in the inhibitory condition). Overall analysis conducted with a random-effects model for the Stroop task ($p < .001$) and for the Go-No/Go task ($p = .76$). The diamonds represent pooled standardised mean difference estimate of random-effects meta-analysis; I^2 represents the heterogeneity test; squares represent study-specific estimates; green circles represent low risk of bias; red circles represent high risk of bias; and the empty space represents unclear risk of bias.

CI [–1.79, 1.30], $p = .76$, $d = .59$). There was considerable heterogeneity in the overall analysis of cognitive training on the Go/No-Go task ($I^2 = 92\%$, $Tau^2 = 1.15$). In an overall analysis (without comparison of subgroups and tests) the meta-analysis did not show statistical significance ($n = 118$, $SMD = .42$, *CI* [–0.27, 1.11], $p = .76$, $I^2 = 84\%$, $Tau^2 = .50$).

Effects on working memory

The effects of cognitive training on working memory were evaluated in ten trials (Ballesteros et al., 2014; Basak et al., 2008; Grönholm-Nyman et al., 2017; Jaeggi et al., 2020; Kazazi et al., 2021; Lee et al., 2020; Nouchi et al., 2019; Perrot et al., 2019, Shatil et al., 2014; Weicker et al., 2018), which were measured by the Digit Span (Forward and Backward), N-Back, and Corsi Blocks tasks. The meta-analysis on working memory measured by the Digit Span Task—Forward showed a marginal statistical significance (overall effect) in favour of cognitive training intervention when compared to active/

passive controls (see first forest plot in Figure 3; $n = 259$ participants, $SMD = 2.78$, CI [−0.07, 5.62], $p = .06$, $d = .92$). There was considerable heterogeneity in the overall analysis ($I^2 = 98\%$, $Tau^2 = 8.27$). The meta-analysis resulted in a statistical significance (subgroup effect) in favour of the cognitive training when compared to the passive control ($n = 40$ participants, $SMD = 2.70$, CI [1.82, 3.57], $p < .001$, $d = .09$), although such output was solely based on one trial; and significance was not achieved when cognitive training was compared to active control group ($n = 219$ participants, $SMD = 2.81$, CI [−0.98, 6.61], $p = .15$, $d = .93$, $I^2 = 99\%$, $Tau^2 = 11.10$).

The meta-analysis on working memory by Digit Span—Backward did not show significance (overall effect) in favour of cognitive training intervention when compared to active/passive controls (see second forest plot in Figure 3; $n = 292$ participants, $SMD = .45$, CI [−2.05, 2.96], $p = .72$, $d = .95$). There was also considerable heterogeneity in the overall analysis ($I^2 = 98\%$, $Tau^2 = 7.99$). The meta-analysis resulted in a statistical significance (subgroup effect) in favour of the passive control when compared to the cognitive training ($n = 40$ participants, $SMD = -2.57$, CI [−3.43, −1.72], $p < .001$, $d = .06$), although such output showed a small size effect and was solely based on one trial.

The meta-analysis on working memory measured by the Corsi Blocks task showed a statistical significance (overall effect) in favour of cognitive training intervention when compared to active/passive controls (see third forest plot in Figure 3; $n = 133$ participants, $SMD = 2.28$, CI [.84, 3.73], $p = .002$, $d = .16$). There was considerable heterogeneity in the overall analysis ($I^2 = 90\%$, $Tau^2 = 1.93$). This large heterogeneity could be a result of the outcome of the second study of Weicker et al. (2018), since a reduced heterogeneity ($I^2 = 51\%$, $Tau^2 = .18$) was observed without the data of Weicker et al. (2018) and the overall effect remained significant. The subgroup effects showed near significance and statistical difference in favour of cognitive training when compared to active ($n = 80$ participants, $SMD = 3.19$, CI [−0.42, 6.79], $p = .08$, $d = .57$, $I^2 = 96\%$, $Tau^2 = 6.48$) and passive controls ($n = 53$ participants, $SMD = 1.49$, CI [.22, 2.76], $p = .02$, $d = .25$, $I^2 = 75\%$, $Tau^2 = .63$), respectively.

The meta-analysis on working memory measured by the N-Back task did not show statistical significance (overall effect; see fourth forest plot in Figure 3): $n = 442$ participants, $SMD = -1.62$, CI [−3.54, .30], $p = .10$, $d = .26$). There was considerable heterogeneity in the overall analysis ($I^2 = 98\%$; $Tau^2 = 7.38$). Interestingly, results showed a marginal subgroup effect in favour of the active control when compared to the cognitive training ($n = 118$ participants, $SMD = -5.47$, CI [−10.98, .04], $p = .05$, $d = 1.04$, $I^2 = 98\%$; $Tau^2 = 23.02$). In an overall analysis (without comparison of subgroups and tests) the meta-analysis did not show statistical significance ($n = 565$, $SMD = .49$, CI [−0.60, 1.57], $p = .38$, $I^2 = 98\%$, $Tau^2 = 6\ .18$).

Effects on cognitive flexibility

The effects of cognitive training on cognitive flexibility were evaluated in five trials (Grönholm-Nyman et al., 2017; Schoene et al., 2015; Shatil et al., 2014; Simon et al., 2018; Van Het Reve & De Bruin, 2014), which were measured by the Trail Making Task—Part B, and Semantic Fluency tasks. The meta-analysis on cognitive flexibility measured by the Trail Making Task—Part B did not show

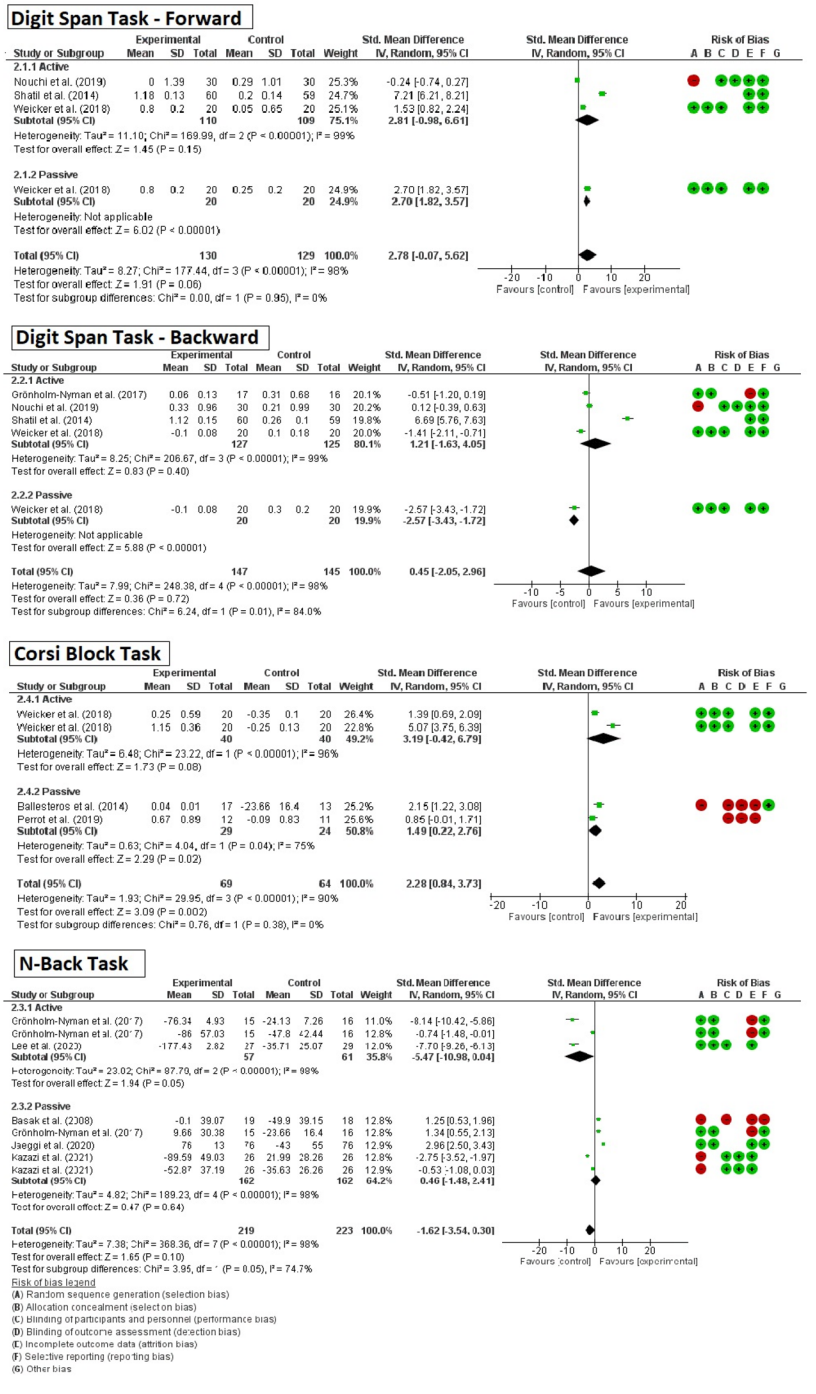

Figure 3. Working memory measured by the Digit Span, Corsi Block, and N-back tasks.

Notes. Standardised mean difference effects of cognitive training compared with active/passive controls on working memory outcomes in healthy older adults measured by the Digit Span – Forward and Backward (score), Corsi Block (score), and N-Back (reaction time) tasks. Overall analysis conducted with a random-effects model for the Digit Span Task – Forward (p = .06), Digit Span – Backward (p = .72), Corsi Block (p = .002), and N-Back (p = .10) tasks. The diamonds represent pooled standardised mean difference estimate of random-effects meta-analysis; I^2 represents the heterogeneity test; squares represent study-specific estimates; green circles represent low risk of bias; red circles represent high risk of bias and the empty space represents unclear risk of bias.

statistical significance (overall effect) in favour of cognitive training intervention when compared to active/passive controls (Figure 4 upper half; $n = 458$ participants, $SMD = -.59$, CI [−1.25, .08], $p = .08$, $d = .27$). There was considerable heterogeneity in the overall analysis ($I^2 = 91\%$; $Tau^2 = .52$). The meta-analysis resulted in a statistical significance (subgroup effect) in favour of the passive control when compared to the cognitive training ($n = 81$ participants, $SMD = -0.53$, CI [−0.98, −0.09], $p = .02$, $d = .33$), although such output was solely based on one trial; and significance was not achieved when active control group was compared to cognitive training group ($n = 377$ participants, $SMD = -0.59$, CI [−1.44, .26], $p = .17$, $d = .11$, $I^2 = 93\%$, $Tau^2 = .69$).

The meta-analysis on cognitive flexibility measured by Semantic Fluency tasks did not show statistical significance (overall effect) in favour of cognitive training intervention when compared to the active controls (Figure 4 bottom half; $n = 115$ participants, $SMD = -1.90$, CI [−7.28, 3.47], $p = .49$, $d = .06$). There was considerable heterogeneity in the overall analysis ($I^2 = 99\%$; $Tau^2 = 14.89$). In an overall analysis (without comparison of subgroups and tests) the meta-analysis showed a marginal statistical significance ($n = 283$, $SMD = .92$, CI [−1.85, .00], $p = .05$, $I^2 = 96\%$, $Tau^2 = 1.48$).

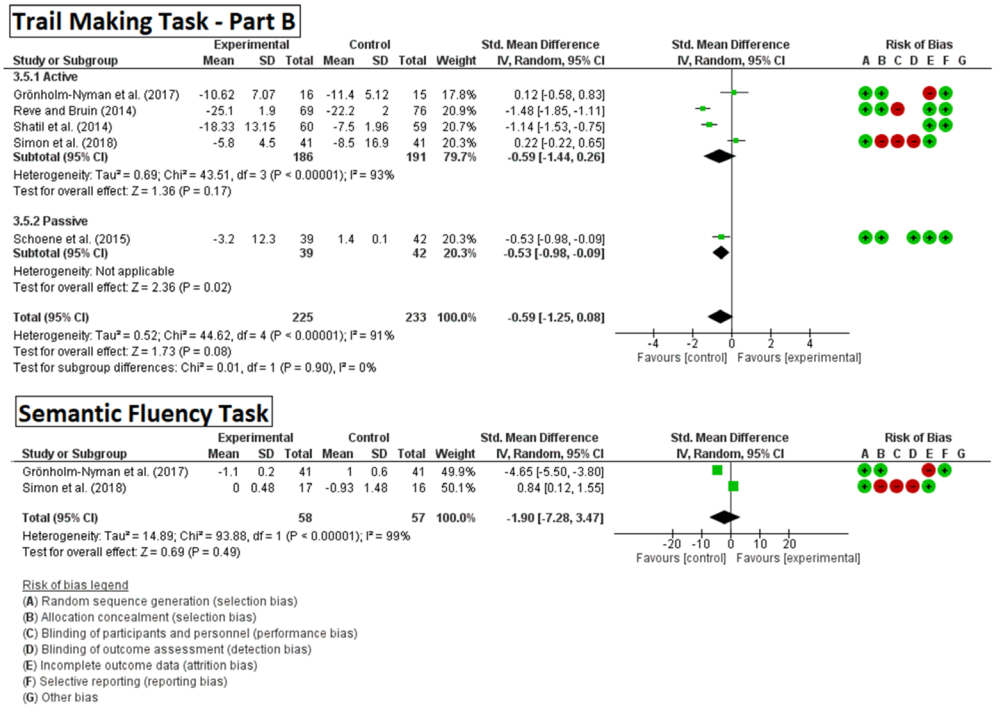

Figure 4. Cognitive flexibility measured by the Trail Making Task – Part B and Semantic Fluency tasks.

Notes. Standardised mean difference effects of cognitive training compared with active/passive controls on cognitive flexibility outcomes in healthy older adults measured by the Trail Making Task – Part B (score in seconds) and Semantic Fluency tasks (score in seconds). Overall analysis conducted with a random-effects model for the Trail Making Task – Part B ($p = .08$) and Semantic Fluency Task ($p = .49$). The diamonds represent pooled standardised mean difference estimate of random-effects meta-analysis; I^2 represents the heterogeneity test; squares represent study-specific estimates; green circles represent low risk of bias; red circles represent high risk of bias and the empty space represents unclear risk of bias.

Methodological quality assessment

The methodological quality was assessed in the thirteen trials included in the meta-analysis. The trials of Lee et al. (2020), Nouchi et al. (2019) and Weicker et al. (2018) had the highest score in the seven categories (Figure 5). The categories *incomplete outcome data* and *selective reporting* had a higher percentage of trials with low risk of bias (Figure 6).

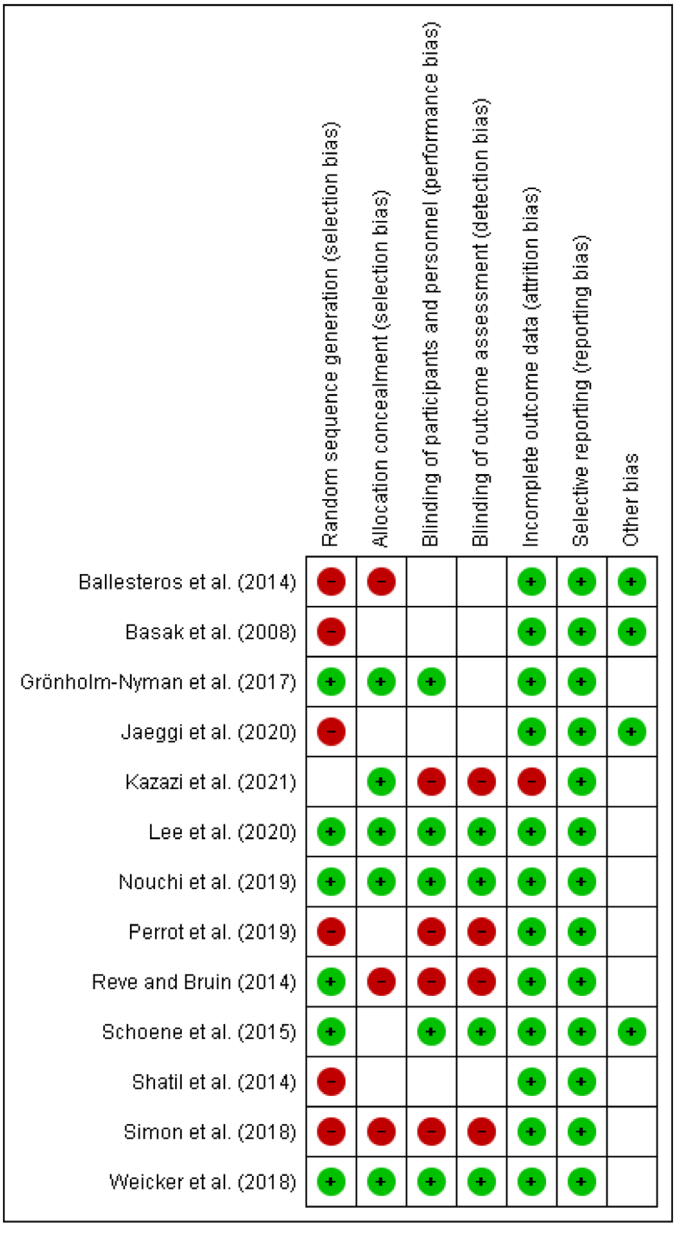

Figure 5. Risk of bias summary: Review authors' judgements about each risk of bias item for each included trial.

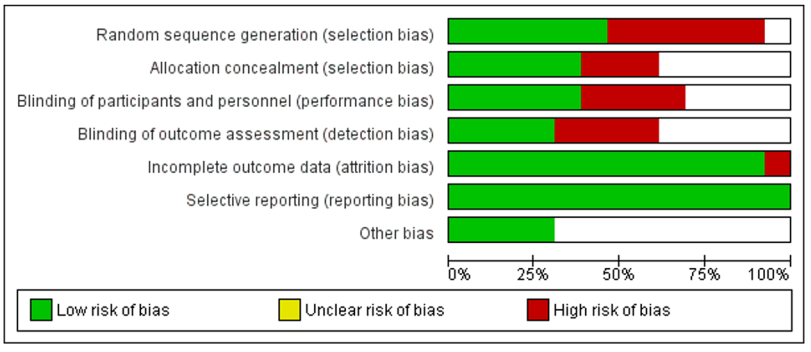

Figure 6. Risk of bias graph: Review authors' judgements about each risk of bias item presented as percentages across all included studies.

Discussion

The aim of the present systematic review with meta-analysis was to assess the efficacy of cognitive training on executive functions in healthy older people. The theoretical framework that proposes a core triad of cognitive functions (Diamond, 2013; Lehto et al., 2003; Miyake et al., 2000) was adopted to segment the meta-analysis in its subdomains (inhibitory control, working memory, and cognitive flexibility). We considered different modalities of cognitive training (e.g. multidomain/single domain training and combined interventions). However, we provided a fine-tuned control over the outcomes and, as far as we know, this is the first review with task-specific meta-analytic data targeting executive functions in older people. For the investigation of cognitive training efficacy in inhibitory control, we adopted the Stroop and Go/No-Go tasks; for working memory, we adopted the Digit Span (forward and backward), Corsi Blocks, and N-Back tasks; and for cognitive flexibility, we adopted the Trail Making—Part B and Semantic Fluency tasks. Our search obtained 21 trials that evaluated inhibitory control, 27 trials that evaluated working memory, and 21 trials that evaluated cognitive flexibility in the systematic review. Most of the selected trials also assessed other cognitive functions (e.g. language, processing speed, general cognition). Thirteen trials were considered for the meta-analysis, which resulted in mixed evidence for the subdomains inhibitory control and working memory, and no evidence of improvement for cognitive flexibility.

The evidence regarding the cognitive gains of cognitive training in executive functions is also mixed when we consider the first meta-analyses that investigated the main cognitive functions in healthy older adults. The review conducted by Lampit et al. (2014) selected 29 randomized controlled trials and found no significant effect for executive functions (p = .96; g = .09). Conversely, Chiu et al. (2017) found a small effect size for executive functions (p < .001; g = .42) in 14 randomized controlled trials. Further reviews then broke down executive subdomains in their analyses, and so do we.

Effects on inhibitory control

Our task-specific meta-analysis on inhibitory control measured by the Stroop task resulted in a statistical significance (p < .001; d = 1.64) in favour of cognitive training

when compared to controls. Despite the low quantity, the studies considered for analysis on active control showed high methodological quality; and cognitive training improved the outcomes on the Stroop task when compared to both passive and active controls. In addition, low heterogeneity and high effect size were observed. However, cognitive training did not improve the outcomes on the Go/No-Go task. This may be related to the duration of the intervention (see Chiu et al., 2017). The total number of training hours was 52.9% higher in the studies selected for meta-analysis of the Stroop task outcomes compared to the studies selected for the Go/No-Go task outcomes. As new studies are carried out, characteristics of cognitive training such as training duration should be considered in the future meta-analyses.

Two previous reviews segmented the analysis by executive function subdomains (inhibitory control included). Nguyen et al. (2019) examined the efficacy of single- and multidomain cognitive training targeting executive functions in healthy older people. The study was not limited to randomized controlled trials and considered 13 studies for near-transfer inhibitory control outcomes. The results showed a significant difference in favour of the cognitive training and a small effect size (p = .048; g = .13). The study by Wollesen et al. (2020) investigated the effectiveness of cognitive-motor training on executive functions in older people. Eleven randomized controlled trials entered the meta-analysis that showed that the intervention enhanced inhibitory control (SMD = .61; p < .001). Taking all the results together, it is highly plausible to assume that inhibitory control can present a mild-to-moderate enhancement by cognitive training in older adults.

Effects on working memory

We also obtained mixed results on working memory outcomes. The meta-analysis on working memory measured by the Digit Span task—Forward showed a marginal statistical significance in favour of the cognitive training when compared to controls (p = .06, d = .92), and no difference was observed in the Digit Span task—Backwards (p = .72, d = .95), and in the N-Back task (p = .10, d = .26). It is likely that more complex tasks (i.e. Digit Span—Backwards and N-Back) would require more training for any cognitive improvement than simpler tasks (i.e. Digit Span—Forward). Thus, likewise for inhibitory control, the duration of the training may play a role in cognitive gains. The near-transfer observed in the Corsi Blocks task in the present work (p = .002, d = .16) may be seen as an argument for the training duration influence. The total number of training hours was 21.3% higher in the studies selected for meta-analysis of Corsi Blocks task outcomes (significant in favour of the cognitive training) compared to the studies selected for Digit Span—Backward and N-Back task outcomes (non-significant results). In addition, classic designs of Digit Span tasks require free recall of numbers, while classic designs of Corsi Blocks tasks require recognition of spatial locations visually available. Therefore, Corsi Blocks is generally an easier task than Digit Span.

Another route of explanation is related to the nature of the task: verbal vs. spatial. Our results showed an improvement in working memory due to cognitive training in a spatial task (i.e. Corsi Blocks) but not in verbal tasks (i.e. Digit Span—Backward and N-Back[3]). Most influential models of working memory support distinct visuospatial and verbal subsystems (Baddeley, 1986; Luck & Vogel, 1997; Smith et al., 1996) which

are linked to functional disparities. For instance, participants are usually worse in the backward than forward version of the Digit Span, but they have similar performance in backward and forward versions of the Corsi Blocks (Donolato et al., 2017). The distinction between the two subsystems was also observed in its neural basis since visuospatial and verbal working memory activate different brain areas (Chein et al., 2011; Nagel et al., 2013). Considering the literature and our results, it is reasonable to presume that one working memory subsystem may be more prone to enhancement from cognitive training than the other.

Previous reviews also investigated the effect of cognitive training on working memory in healthy older adults. Wollesen et al. (2020) entered five randomized controlled trials in the meta-analysis, and there was no effect on working memory (p = .19). Three other reviews (Chiu et al., 2017; Lampit et al., 2014; Nguyen et al., 2019) showed significant differences favouring the cognitive training over controls but with small effect sizes (20–45 studies entered the meta-analyses; all $p < .001$ and $.22 < g < .35$). The meta-analysis of Chiu et al. (2017) considered overall memory outcomes, including short-term memory and working memory; and the meta-analysis of Nguyen et al. (2019) considered short-term memory and working memory. The high heterogeneity observed in the Digit Span and N-Back meta-analysis (I^2 = 98%) hamper the conclusions. Nevertheless, considering our results and previous reviews in older adults, it is plausible to assume that cognitive training causes a near-transfer for some tasks that may present a none-to-mild enhancement in working memory.

Effects on cognitive flexibility

Both the meta-analysis on cognitive flexibility measured by the Trail Making task—Part B and Semantic Fluency tasks did not show statistical significance in favour of cognitive training intervention when compared to controls ($p > .08$; $d < .11$). Wollesen et al. (2020) entered five randomized controlled trials in the meta-analysis, and also found no effect on cognitive flexibility (p = .09). Nguyen et al. (2019) considered 13 studies, and the analysis revealed a significant difference in favour of the cognitive training and a small effect size for the cognitive flexibility outcomes (p = .031; $g = 0.16$). The few studies altogether support the idea that cognitive flexibility can present a none-to-mild enhancement by cognitive training in older adults.

Clinical considerations

In the very best scenario considering the current knowledge, cognitive training is likely to provide up to moderate enhancement of executive functions in healthy older adults. Thus, health professionals should whenever possible keep recommending other interventions that have been proven to maintain or boost general cognition and executive functions: physical activity, healthy diet, social and meaningful connections, and daily-life complex cognitive tasks (Dominguez et al., 2021; Kelly et al., 2017; Newson & Kemps, 2006). Nevertheless, despite the modest results, the area must maintain efforts to investigate a low-cost non-invasive and highly flexible behavioural

intervention. Possibly, the plurality of interventions and outcomes seen in cognitive training may produce a fog in the literature of this very recent area.

Although our review summarized studies were carried out in healthy older adults, it may also have implications for clinical populations. For instance, executive dysfunction can be present in the early stages of Parkinson's disease. The most frequent neuropsychological alterations range from mild executive dysfunction in the early stages to mild cognitive impairment, and then dementia in the later stages (Dirnberger & Jahanshahi, 2013). Thus, the implementation of cognitive training focusing on executive functions can be adopted as a complementary treatment in an attempt to delay neuropsychological impairments. Similarly, people living with HIV experience cognitive decline, including in executive functions (Kanmogne et al., 2018). Previous research has shown that cognitive training is associated with improvements in cognitive and daily function among this population, and has suggested that better results occur after longer cognitive training sessions (Wei et al., 2022). Finally, when dealing with older adults, it is necessary to consider the limitations of these individuals when it comes to mobility and sensorial loss, in addition to age-adjusted task complexity and cognitive load.

Highlights, limitations, and future directions

This study is the first review with task-specific meta-analytic data targeting executive functions in older people. We believe that a fine-tuned control over the outcomes provides better clarity regarding the efficacy of cognitive training interventions, and hence helps professionals and decision makers who seek for reviews with detailed data and higher degrees of specificity. Given that the world's population is aging faster than ever before and that innovative approaches to improving the quality of life of older people have been investigated in the literature, this study provides an overview of prospective experimental design data (e.g. dose, sessions, length, tests) for the implementation of cognitive training programmes targeting executive functions in healthy older adults, as well as the subdomains of executive functions with greater and less effectiveness, according to the literature. In addition, for the present review we conducted the search in databases and directories not considered in previous reviews with meta-analysis that investigated the effect of cognitive training on executive functions in older adults (Chiu et al., 2017; Lampit et al. 2014; Nguyen et al., 2019; Wollesen et al., 2020); they were: Scielo, Web of Science, Lens.org, epistemonikos.org, and cognitivetrainingdata.org.

Since we had tight control over the cognitive training outcomes in the pre- and post-testing, we ran meta-analyses with few studies. Our study also presents a limitation regarding the types of the selected trials. We have not restricted combined trials (i.e. cognitive training plus a second intervention), and we made no distinction regarding the type of training sessions (simultaneous or sequential training), the duration of the sections, and the cognitive function trained (single-domain or multi-domain training). In addition, the present review only compared data of pre- and post-training. Future investigations may tackle long-term efficacy of task-specific gains in executive function in older people.

Hopefully, as new trials are published and accumulate, it would be optimal to obtain task-specific meta-analytic data segmented by efficacy duration (immediate and long-term), type of transfer (i.e. near and far), and type of outcome. In particular, it would be of great interest to obtain results on ecologically-validated outcomes due to the close relation of executive functions and functional everyday life activities.

Conclusion

The present review on the effect of cognitive training for healthy older adults showed mixed evidence for inhibitory control and working memory enhancement, and no evidence of improvement for cognitive flexibility.

Notes

1. A passive control group refers to protocol with no intervention between pre- and post-testing (i.e. no-contact control group). An active control group refers to protocol with an intervention, ideally with similar topography of the experimental group's intervention, but planned to promote no enhancement in the cognitive processes of interest that is evaluated in the pre- and post-testing (e.g. playing Sudoku when the experimental intervention seeks to promote gains in inhibitory control) in order to control placebo-like effects of the cognitive training.
2. The Stroop task assesses the ability to inhibit cognitive interference, which occurs when the processing of a stimulus feature simultaneously affects the processing of another attribute of the same stimulus (Scarpina & Tagini, 2017). The Go/No-Go task involves a series of decisions in which participants are asked to respond to one class of stimuli, that is, the go stimuli, but not to another class of stimuli, that is, the no-go stimuli (Young et al., 2018). The Digit Span task involves reading out a series of strings of digits to the participants who are required to repeat them in the same or reverse order of presentation (i.e. forward and backward conditions; Tripathi et al., 2019). In the N-Back task participants are presented a series of visual stimuli and they are asked for each stimulus whether it matches a stimulus *n* positions before, which requires maintaining continuous updating and processing of information (Gajewski et al., 2018). The Corsi Block consists of a surface of scattered blocks in which the examiner taps a sequence of blocks and the participant has to repeat the sequence in the same order or backwards (Kessels et al., 2000). In the Trail Making – Part B, subjects connect 25 encircled numbers and letters in numerical and alphabetical order, alternating between numbers and letters (Linari et al., 2022). In the Semantic Fluency tasks the individuals are required to recall items. Some variations of this test include the fluency of certain classes of words or different semantic categories such as animals and fruits (Lopes et al., 2009).
3. From the total of 5 trials that entered the N-Back task meta-analysis, two used pictorial stimuli instead of verbal stimuli (Jaeggi et al., 2020; Kazazi et al., 2021). Both trials compared the cognitive training to passive controls and account for a small treatment effect (*SMD* = .32).

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Search strategy, data obtained from databases and directories, data extracted for meta-analysis, and outputs of all analyses are available at https://osf.io/64xmj/.

References

(References marked with asterisk (*) indicate studies included in the meta-analysis.)

Abd-Alrazaq, A., Alhuwail, D., Ahmed, A., & Househ, M. (2022). Effectiveness of serious games for improving executive functions among older adults with cognitive impairment: Systematic review and meta-analysis. *JMIR Serious Games*, *10*(3), e36123. https://doi.org/10.2196/36123

Adcock, M., Fankhauser, M., Post, J., Lutz, K., Zizlsperger, L., Luft, A. R., Guimarães, V., Schättin, A., & de Bruin, E. D. (2019). Effects of an in-home multicomponent exergame training on physical functions, cognition, and brain volume of older adults: A randomized controlled trial. *Frontiers in Medicine*, *6*(1), 321. https://doi.org/10.3389/fmed.2019.00321

Alexopoulos, G. S., Meyers, B. S., Young, R. C., Kalayam, B., Kakuma, T., Gabrielle, M., Sirey, J. A., & Hull, J. W. (2000). Executive dysfunction and long-term outcomes of geriatric depression. *Archives of General Psychiatry*, *57*(3), 285–290. https://doi.org/10.1001/archpsyc.57.3.285

Anguera, J. A., Volponi, J. J., Simon, A. J., Gallen, C. L., Rolle, C. E., Anguera-Singla, R., Pitsch, E. A., Thompson, C. J., & Gazzaley, A. (2022). Integrated cognitive and physical fitness training enhances attention abilities in older adults. *Npj Aging*, *8*(1), 12. https://doi.org/10.1038/s41514-022-00093-y

Baddeley, A. D. (1986). *Working memory*. Oxford University Press.

*Ballesteros, S., Prieto, A., Mayas, J., Toril, P., Pita, C., de León, L. P., Reales, J. M., & Waterworth, J. (2014). Brain training with non-action video games enhances aspects of cognition in older adults: A randomized controlled trial. *Frontiers in Aging Neuroscience*, *6*(10), 277. https://doi.org/10.3389/fnagi.2014.00277

*Basak, C., Boot, W. R., Voss, M. W., & Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychology and Aging*, *23*(4), 765–777. https://doi.org/10.1037/a0013494

Bergman Nutley, S., & Söderqvist, S. (2017). How is working memory training likely to influence academic performance? Current evidence and methodological considerations. *Frontiers in Psychology*, *8*(8), 69. https://doi.org/10.3389/fpsyg.2017.00069

Boot, W. R., Simons, D. J., Stothart, C., & Stutts, C. (2013). The pervasive problem with placebos in psychology: Why active control groups are not sufficient to rule out placebo effects. *Perspectives on Psychological Science*, *8*(4), 445–454. https://doi.org/10.1177/1745691613491271

Caswell, H., & Zarulli, V. (2018). Matrix methods in health demography: A new approach to the stochastic 777analysis of healthy longevity and DALYs. *Population Health Metrics*, *16*(1), 8. https://doi.org/10.1186/s12963-018-0165-5

Coppin, A. K., Shumway-Cook, A., Saczynski, J. S., Patel, K. V., Ble, A., Ferrucci, L., & Guralnik, J. M. (2006). Association of executive function and performance of dual-task physical tests among older adults: Analyses from the In Chianti study. *Age and Ageing*, *35*(6), 619–624. https://doi.org/10.1093/ageing/afl107

Corbo, I., & Casagrande, M. (2022). Higher-level executive functions in healthy elderly and mild cognitive impairment: A systematic review. *Journal of Clinical Medicine*, *11*(5), 1204. https://doi.org/10.3390/jcm11051204

Chein, J. M., Moore, A. B., & Conway, A. R. (2011). Domain-general mechanisms of complex working memory span. *NeuroImage*, *54*(1), 550–559. https://doi.org/10.1016/j.neuroimage.2010.07.067

Chiu, H.-L., Chu, H., Tsai, J.-C., Liu, D., Chen, Y.-R., Yang, H.-L., & Chou, K.-R. (2017). The effect of cognitive-based training for the healthy older people: A meta-analysis of randomized controlled trials. *PLoS One*, *12*(5), e0176742. https://doi.org/10.1371/journal.pone.0176742

Cochrane. (2022). Review Manager [Computer Software]. *Cochrane Training*. https://training.cochrane.org/online-learning/core-software/revman/.

Cowan, N. (2014). Working memory underpins cognitive development, learning and education. *Educational Psychology Review*, *26*(2), 197–223. https://doi.org/10.1007/s10648-013-9246-y

Dajani, D. R., & Uddin, L. Q. (2015). Demystifying cognitive flexibility: Implications for clinical and developmental neuroscience. *Trends in Neurosciences*, *38*(9), 571–578. https://doi.org/10.1016/j.tins.2015.07.003

Deeks, J. J., & Higgins, J. P. (2022). Chapter 10: Analysing data and undertaking meta-analyses. In *Cochrane Handbook for Systematic Reviews of Interventions version 6.3* (2nd ed.). John Wiley & Sons, Ltd. https://training.cochrane.org/handbook/current/chapter-10

Demir Akça, A. S., Saraçli, Ö., Emre, U., Atasoy, N., Güdül, S., Özen Barut, B., Şenormanci, Ö., Büyükuysal, M. Ç., Atik, L., & Atasoy, H. T. (2014). Relationship of cognitive functions with daily living activities, depression, anxiety and clinical variables in hospitalized elderly patients. *Noro Psikiyatri Arsivi*, *51*(3), 267–274. https://doi.org/10.4274/npa.y7053

Desjardins, L. C., Berryman, N., Fraser, S. A., Vu, T. T. M., KErgoat, Ma, J., Li, K. Z., Bosquet, L., & Bherer, L. (2016). Effects of combined physical and cognitive training on fitness and neuropsychological outcomes in healthy older adults. *Clinical Interventions in Aging*, *11*, 1287–1299. https://doi.org/10.2147/CIA.S115711

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Dirnberger, G., & Jahanshahi, M. (2013). Executive dysfunction in Parkinson's disease: A review. *Journal of Neuropsychology*, *7*(2), 193–224. https://doi.org/10.1111/jnp.12028

Dominguez, L. J., Veronese, N., Vernuccio, L., Catanese, G., Inzerillo, F., Salemi, G., & Barbagallo, M. (2021). Nutrition, physical activity, and other lifestyle factors in the prevention of cognitive decline and dementia. *Nutrients*, *13*(11), 4080. https://doi.org/10.3390/nu13114080

Donolato, E., Giofrè, D., & Mammarella, I. C. (2017). Differences in Verbal and visuospatial forward and backward order recall: A review of the literature. *Frontiers in Psychology*, *8*, 663. https://doi.org/10.3389/fpsyg.2017.00663

Duggan, M., Wang, L., Wilson, J. E., Dittus, R. S., Ely, E. W., & Jackson, J. C. (2017). The relationship between executive dysfunction, depression, and mental health-related quality of life in survivors of critical illness: Results from the BRAIN-ICU investigation. *Journal of Critical Care*, *37*, 72–79. https://doi.org/10.1016/j.jcrc.2016.08.023

Dumas, J. A. (2017). Strategies for preventing cognitive decline in healthy older adults. *The Canadian Journal of Psychiatry*, *62*(11), 754–760. https://doi.org/10.1177/0706743717720691

Eggenberger, P., Schumacher, V., Angst, M., Theill, N., & de Bruin, E. D. (2015). Does multicomponent physical exercise with simultaneous cognitive training boost cognitive performance in older adults? A 6-month randomized controlled trial with a 1-year follow-up. *Clinical Interventions in Aging*, *10*, 1335–1349. https://doi.org/10.2147/CIA.S87732

Estrada-Plana, V., Montanera, R., Ibarz-Estruga, A., March-Llanes, J., Vita-Barrull, N., Guzmán, N., Ros-Morente, A., Ayesa Arriola, R., & Moya-Higueras, J. (2021). Cognitive training with mod-

ern board and card games in healthy older adults: Two randomized controlled trials. *International Journal of Geriatric Psychiatry*, *36*(6), 839–850. https://doi.org/10.1002/gps.5484

Falbo, S., Condello, G., Capranica, L., Forte, R., & Pesce, C. (2016). Effects of physical-cognitive dual task training on executive function and gait performance in older adults: A randomized controlled trial. *BioMed Research International*, *2016*, 5812092–5812012. https://doi.org/10.1155/2016/5812092

Fan, L., & Wang, Y. (2023). The relationship between executive functioning and attention deficit hyperactivity disorder in young children: A cross-lagged study. *Current Psychology*, *42*(25), 21375–21383. https://doi.org/10.1007/s12144-022-03233-5

Fastame, M. C., Mulas, I., Putzu, V., Asoni, G., Viale, D., Mameli, I., & Pau, M. (2022). Executive and motor functions in older individuals with cognitivei impairment. *Behavioral Sciences*, *12*(7), 214. https://doi.org/10.3390/bs12070214

Ferguson, H. J., Brunsdon, V. E. A., & Bradford, E. E. F. (2021). The developmental trajectories of executive function from adolescence to old age. *Scientific Reports*, *11*(1), 1382. https://doi.org/10.1038/s41598-020-80866-1

Fjell, A. M., Sneve, M. H., Grydeland, H., Storsve, A. B., & Walhovd, K. B. (2017). The disconnected brain and executive function decline in aging. *Cerebral Cortex*, *27*(3), 2303–2317. https://doi.org/10.1093/cercor/bhw082

Foster, L., & Walker, A. (2021). Active ageing across the life course: Towards a comprehensive approach to prevention. *BioMed Research International*, *2021*, 6650414–6650411. https://doi.org/10.1155/2021/6650414

Furlan, A. D., Pennick, V., Bombardier, C., & van Tulder, M. (2009). 2009 updated method guidelines for systematic reviews in the Cochrane Back Review Group. *Spine*, *34*(18), 1929–1941. https://doi.org/10.1097/BRS.0b013e3181b1c99f

Gajewski, P. D., Hanisch, E., Falkenstein, M., Thönes, S., & Wascher, E. (2018). What does the n-Back task measure as we get older? Relations between working-memory measures and other cognitive functions across the lifespan. *Frontiers in Psychology*, *9*(11), 2208. https://doi.org/10.3389/fpsyg.2018.02208

Gajewski, P. D., Thönes, S., Falkenstein, M., Wascher, E., & Getzmann, S. (2020). Multidomain cognitive training transfers to attentional and executive functions in healthy older adults. *Frontiers in Human Neuroscience*, *14*(11), 586963. https://doi.org/10.3389/fnhum.2020.586963

Gamage, M., Hewage, C., & Pathirana, K. (2018). Effect of cognitive and executive functions on perception of quality of life of cognitively normal elderly people dwelling in residential aged care facilities in Sri Lanka. *BMC Geriatrics*, *18*(1), 256. https://doi.org/10.1186/s12877-018-0937-6

Ge, S., Zhu, Z., Wu, B., & McConnell, E. S. (2018). Technology-based cognitive training and rehabilitation interventions for individuals with mild cognitive impairment: A systematic review. *BMC Geriatrics*, *18*(1), 213. https://doi.org/10.1186/s12877-018-0893-1

Giuli, C., Papa, R., Lattanzio, F., & Postacchini, D. (2016). The effects of cognitive training for elderly: Results from my mind project. *Rejuvenation Research*, *19*(6), 485–494. https://doi.org/10.1089/rej.2015.1791

Golino, M. T. S., & Flores-Mendoza, C. E. (2016). Development of a cognitive training program for the elderly. *Revista Brasileira de Geriatria e Gerontologia*, *19*(5), 769–785. https://doi.org/10.1590/1809-98232016019.150144

*Grönholm-Nyman, P., Soveri, A., Rinne, J. O., Ek, E., Nyholm, A., Neely, A. S., & Laine, M. (2017). Limited effects of set shifting training in healthy older adults. *Frontiers in Aging Neuroscience*, *9*(3), 69. https://doi.org/10.3389/fnagi.2017.00069

Harada, C. N., Natelson Love, M. C., & Triebel, K. L. (2013). Normal cognitive aging. *Clinics in Geriatric Medicine*, *29*(4), 737–752. https://doi.org/10.1016/j.cger.2013.07.002

Hardcastle, C., Hausman, H. K., Kraft, J. N., Albizu, A., O'Shea, A., Boutzoukas, E. M., Evangelista, N. D., Langer, K., Van Etten, E. J., Bharadwaj, P. K., Song, H., Smith, S. G., Porges, E., DeKosky, S. T., Hishaw, G. A., Wu, S. S., Marsiske, M., Cohen, R., Alexander, G. E., & Woods, A. J. (2022). Proximal improvement and higher-order resting state network change after multidomain cognitive training intervention in healthy older adults. *GeroScience*, *44*(2), 1011–1027. https://doi.org/10.1007/s11357-022-00535-1

*Jaeggi, S. M., Buschkuehl, M., Parlett-Pelleriti, C. M., Moon, S. M., Evans, M., Kritzmacher, A., Reuter-Lorenz, P. A., Shah, P., & Jonides, J. (2020). Investigating the effects of spacing on working memory training outcome: A randomized, controlled, multisite trial in older adults. *The Journals of Gerontology*, *75*(6), 1181–1192. https://doi.org/10.1093/geronb/gbz090

Jaul, E., & Barron, J. (2017). Age-related diseases and clinical and public health implications for the 85 years old and over population. *Frontiers in Public Health*, *5*, 335. https://doi.org/10.3389/fpubh.2017.00335

Kang, W., Wang, J., & Malvaso, A. (2021). Inhibitory control in aging: The compensation-related utilization of neural circuits hypothesis. *Frontiers in Aging Neuroscience*, *13*, 771885. https://doi.org/10.3389/fnagi.2021.771885

Kanmogne, G. D., Fonsah, J. Y., Tang, B., Doh, R. F., Kengne, A. M., Umlauf, A., Tagny, C. T., Nchindap, E., Kenmogne, L., Franklin, D., Njamnshi, D. M., Mbanya, D., Njamnshi, A. K., & Heaton, R. K. (2018). Effects of HIV on executive function and verbal fluency in Cameroon. *Scientific Reports*, *8*(1), 17794. https://doi.org/10.1038/s41598-018-36193-7

*Kazazi, L., Shati, M., Mortazavi, S. S., Nejati, V., & Foroughan, M. (2021). The impact of computer-based cognitive training intervention on the quality of life among elderly people: A randomized clinical trial. *Trials*, *22*(1), 51. https://doi.org/10.1186/s13063-020-05008-4

Kelly, M. E., Duff, H., Kelly, S., McHugh Power, J. E., Brennan, S., Lawlor, B. A., & Loughrey, D. G. (2017). The impact of social activities, social networks, social support and social relationships on the cognitive functioning of healthy older adults: A systematic review. *Systematic Reviews*, *6*(1), 259. https://doi.org/10.1186/s13643-017-0632-2

Kessels, R. P., van Zandvoort, M. J., Postma, A., Kappelle, L. J., & de Haan, E. H. (2000). The Corsi block-tapping task: Standardization and normative data. *Applied Neuropsychology*, *7*(4), 252–258. https://doi.org/10.1207/S15324826AN0704_8

Klimova, B. (2016). Computer-based cognitive training in aging. *Frontiers in Aging Neuroscience*, *8*, 313. https://doi.org/10.3389/fnagi.2016.00313

Kujawski, S., Kujawska, A., Perkowski, R., Androsiuk-Perkowska, J., Hajec, W., Kwiatkowska, M., Skierkowska, N., Husejko, J., Bieniek, D., Newton, J. L., Morten, K. J., Zalewski, P., & Kędziora-Kornatowska, K. (2021). Cognitive function changes in older people. Results of second wave of cognition of older people, education, recreational activities, nutrition, co-morbidities, functional capacity studies (COPERNICUS). *Frontiers in Aging Neuroscience*, *13*, 653570. https://doi.org/10.3389/fnagi.2021.653570

Lampit, A., Hallock, H., & Valenzuela, M. (2014). Computerized cognitive training in cognitively healthy older adults: A systematic review and meta-analysis of effect modifiers. *PLoS Medicine*, *11*(11), e1001756. https://doi.org/10.1371/journal.pmed.1001756

Langeard, A., Torre, M. M., & Temprado, J.-J. (2021). A dual-task paradigm using the oral Trail Making Test while walking to study cognitive-motor interactions in older adults. *Frontiers in Aging Neuroscience*, *13*, 712463. https://doi.org/10.3389/fnagi.2021.712463

Lazarus, N. R., & Harridge, S. D. R. (2018). The inherent human aging process and the facilitating role of exercise. *Frontiers in Physiology*, *9*, 1135. https://doi.org/10.3389/fphys.2018.01135

*Lee, H. K., Kent, J. D., Wendel, C., Wolinsky, F. D., Foster, E. D., Merzenich, M. M., & Voss, M. W. (2020). Home-based, adaptive cognitive training for cognitively normal older adults: Initial efficacy trial. *The Journals of Gerontology*, *75*(6), 1144–1154. https://doi.org/10.1093/geronb/gbz073

Legault, I., & Faubert, J. (2012). Perceptual-cognitive training improves biological motion perception: Evidence for transferability of training in healthy aging. *Neuroreport*, *23*(8), 469–473. https://doi.org/10.1097/WNR.0b013e328353e48a

Lehto, J. E., Juujärvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology*, *21*(1), 59–80. https://doi.org/10.1348/026151003321164627

Li, H., Goldin, P., & Siegle, G. J. (2022). Neuroscience for clinicians: Translational clinical neuroscience to inspire clinical practice and research. In *Reference module in neuroscience and biobehavioral psychology* (pp. 145–167). Elsevier. https://doi.org/10.1016/B978-0-12-818697-8.00190-4

Li, N., Chen, G., Xie, Y., & Chen, Z. (2021). Aging effect on visuomotor adaptation: Mediated by cognitive decline. *Frontiers in Aging Neuroscience*, *13*, 742928. https://doi.org/10.3389/fnagi.2021.742928

Lima-Silva, T. B., Fabrício, A. T., Silva, L. D. S. V. E., de Oliveira, G. M., da Silva, W. T., Kissaki, P. T., da Silva, A. P. F., Sasahara, T. F., Ordonez, T. N., de Oliveira, T. B., Aramaki, F. O., Buriti, A., & Yassuda, M. S. (2012). Training of executive functions in healthy elderly: Results of a pilot study. *Dementia & Neuropsychologia*, *6*(1), 35–41. https://doi.org/10.1590/S1980-57642012DN06010006

Linari, I., Juantorena, G. E., Ibáñez, A., Petroni, A., & Kamienkowski, J. E. (2022). Unveiling trail making test: Visual and manual trajectories indexing multiple executive processes. *Scientific Reports*, *12*(1), 14265. https://doi.org/10.1038/s41598-022-16431-9

Lopes, M., Brucki, S. M. D., Giampaoli, V., & Mansur, L. L. (2009). Semantic Verbal Fluency test in dementia: Preliminary retrospective analysis. *Dementia & Neuropsychologia*, *3*(4), 315–320. https://doi.org/10.1590/S1980-57642009DN30400009

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281. https://doi.org/10.1038/36846

Makin, S. (2016). Brain training: Memory games. *Nature*, *531*(7592), S10–S11. https://doi.org/10.1038/531S10a

Maldonado Briegas, J. J., Sánchez Iglesias, A. I., Ballester, S. G., & Vicente Castro, F. (2020). The well-being of the elderly: Memory and aging. *Frontiers in Psychology*, *11*, 778. https://doi.org/10.3389/fpsyg.2020.00778

Melsen, W. G., Bootsma, M. C., Rovers, M. M., & Bonten, M. J. (2014). The effects of clinical and statistical heterogeneity on the predictive values of results from meta-analyses. *Clinical Microbiology and Infection*, *20*(2), 123–129. https://doi.org/10.1111/1469-0691.12494

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Meltzer, J. A., Kates Rose, M., Le, A. Y., Spencer, K. A., Goldstein, L., Gubanova, A., Lai, A. C., Yossofzai, M., Armstrong, S. E. M., & Bialystok, E. (2023). Improvement in executive function for older adults through smartphone apps: A randomized clinical trial comparing language learning and brain training. *Neuropsychology, Development, and Cognition*, *30*(2), 150–171. https://doi.org/10.1080/13825585.2021.1991262

Mozolic, J. L., Long, A. B., Morgan, A. R., Rawley-Payne, M., & Laurienti, P. J. (2011). A cognitive training intervention improves modality-specific attention in a randomized controlled trial of healthy older adults. *Neurobiology of Aging*, *32*(4), 655–668. https://doi.org/10.1016/j.neurobiolaging.2009.04.013

Murman, D. L. (2015). The impact of age on cognition. *Seminars in Hearing*, *36*(3), 111–121. https://doi.org/10.1055/s-0035-1555115

Nagel, B. J., Herting, M. M., Maxwell, E. C., Bruno, R., & Fair, D. (2013). Hemispheric lateralization of verbal and spatial working memory during adolescence. *Brain and Cognition*, *82*(1), 58–68. https://doi.org/10.1016/j.bandc.2013.02.007

Nguyen, L., Murphy, K., & Andrews, G. (2019). Immediate and long-term efficacy of executive functions cognitive training in older adults: A systematic review and meta-analysis. *Psychological Bulletin*, *145*(7), 698–733. https://doi.org/10.1037/bul0000196

Newson, R. S., & Kemps, E. B. (2006). The influence of physical and cognitive activities on simple and complex cognitive tasks in older adults. *Experimental Aging Research*, *32*(3), 341–362. https://doi.org/10.1080/03610730600699134

Nicholls, V. I., Wiener, J. M., Meso, A. I., & Miellet, S. (2022). The relative contribution of executive functions and aging on attentional control during road crossing. *Frontiers in Psychology*, *13*, 912446. https://doi.org/10.3389/fpsyg.2022.912446

Nouchi, R., Hu, Q., Saito, T., Kawata, N. Y. d S., Nouchi, H., & Kawashima, R. (2021). Brain training and sulforaphane intake interventions separately improve cognitive performance in healthy older adults, whereas a combination of these interventions does not have more beneficial effects: Evidence from a randomized controlled trial. *Nutrients*, *13*(2), 352. https://doi.org/10.3390/nu13020352

*Nouchi, R., Kobayashi, A., Nouchi, H., & Kawashima, R. (2019). Newly developed TV-based cognitive training games improve car driving skills, cognitive functions, and mood in healthy older adults: Evidence from a randomized controlled trial. *Frontiers in Aging Neuroscience*, *11*(5), 99. https://doi.org/10.3389/fnagi.2019.00099

Nouchi, R., Taki, Y., Takeuchi, H., Hashizume, H., Akitsuki, Y., Shigemune, Y., Sekiguchi, A., Kotozaki, Y., Tsukiura, T., Yomogida, Y., & Kawashima, R. (2012). Brain training game improves executive functions and processing speed in the elderly: A randomized controlled trial. *PLoS One*, *7*(1), e29676. https://doi.org/10.1371/journal.pone.0029676

Ouzzani, M., Hammady, H., Fedorowicz, Z., & Elmagarmid, A. (2016). Rayyan-a web and mobile app for systematic reviews. *Systematic Reviews*, *5*(1), 210. https://doi.org/10.1186/s13643-016-0384-4

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *PLoS Medicine*, *18*(3), e1003583. https://doi.org/10.1186/s13643-021-01626-4

Park, H.-A. (2016). Are we ready for the fourth industrial revolution? *Yearbook of Medical Informatics*, *1*(1), 1–3. https://doi.org/10.15265/IY-2016-052

Pascual, A. C., Moyano, N., & Quílez-Robres, A. (2019). The relationship between executive functions and academic performance in primary education: Review and meta-analysis. *Frontiers in Psychology*, *10*, 1582. https://doi.org/10.3389/fpsyg.2019.01582

Peng, Q., Wu, Y., Qie, N., & Iwaki, S. (2022). Age-related effects of executive function on takeover performance in automated driving. *Scientific Reports*, *12*(1), 5410. https://doi.org/10.1038/s41598-022-08522-4

Peretz, C., Korczyn, A. D., Shatil, E., Aharonson, V., Birnboim, S., & Giladi, N. (2011). Computer-based, personalized cognitive training versus classical computer games: A randomized double-blind prospective trial of cognitive stimulation. *Neuroepidemiology*, *36*(2), 91–99. https://doi.org/10.1159/000323950

*Perrot, A., Maillot, P., & Hartley, A. (2019). Cognitive training game versus action videogame: Effects on cognitive functions in older adults. *Games for Health Journal*, *8*(1), 35–40. https://doi.org/10.1089/g4h.2018.0010

Romero-Ferreiro, V., Rodríguez-Gómez, P., Pozo, M. Á., & Moreno, E. M. (2022). Can you change your mind? An ERP study of cognitive flexibility and new evidence integration. *Biological Psychology*, *172*, 108354. https://doi.org/10.1016/j.biopsycho.2022.108354

Sala, G., Aksayli, N. D., Tatlidil, K. S., Gondo, Y., & Gobet, F. (2019). Working memory training does not enhance older adults' cognitive skills: A comprehensive meta-analysis. *Intelligence*, *77*, 101386. https://doi.org/10.1016/j.intell.2019.101386

Sanjuán, M., Navarro, E., & Dolores Calero, M. (2020). Effectiveness of cognitive interventions in older adults: A review. *European Journal of Investigation in Health, Psychology and Education*, *10*(3), 876–898. https://doi.org/10.3390/ejihpe10030063

Scarpina, F., & Tagini, S. (2017). The stroop color and word test. *Frontiers in Psychology*, *8*(4), 557. https://doi.org/10.3389/fpsyg.2017.00557

*Schoene, D., Valenzuela, T., Toson, B., Delbaere, K., Severino, C., Garcia, J., Davies, T. A., Russell, F., Smith, S. T., & Lord, S. R. (2015). Interactive cognitive-motor step training improves cognitive risk factors of falling in older adults – A randomized controlled trial. *PLoS One*, *10*(12), e0145161. https://doi.org/10.1371/journal.pone.0145161

Shatil, E. (2013). Does combined cognitive training and physical activity training enhance cognitive abilities more than either alone? A four-condition randomized controlled trial among healthy older adults. *Frontiers in Aging Neuroscience*, *5*(3), 8. https://doi.org/10.3389/fnagi.2013.00008

*Shatil, E., Mikulecká, J., Bellotti, F., & Bureš, V. (2014). Novel television-based cognitive training improves working memory and executive function. *PLoS One*, *9*(7), e101472. https://doi.org/10.1371/journal.pone.0101472

Shelton, J. T., Elliott, E. M., Hill, B. D., Calamia, M. R., & Gouvier, W. D. (2009). A comparison of laboratory and clinical working memory tests and their prediction of fluid intelligence. *Intelligence*, *37*(3), 283–293. https://doi.org/10.1016/j.intell.2008.11.005

*Simon, S. S., Tusch, E. S., Feng, N. C., Håkansson, K., Mohammed, A. H., & Daffner, K. R. (2018). Is computerized working memory training effective in healthy older adults? Evidence from a multi-site, randomized controlled trial. *Journal of Alzheimer's Disease*, *65*(3), 931–949. https://doi.org/10.3233/JAD-180455

Simons, D. J., Boot, W. R., Charness, N., Gathercole, S. E., Chabris, C. F., Hambrick, D. Z., & Stine-Morrow, E. A. L. (2016). Do "brain-training" programs work? *Psychological Science in the Public Interest*, *17*(3), 103–186. https://doi.org/10.1177/1529100616661983

Smith, E. E., Jonides, J., & Koeppe, R. A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex*, *6*(1), 11–20. https://doi.org/10.1093/cercor/6.1.11

Smith, G. E., Housen, P., Yaffe, K., Ruff, R., Kennison, R. F., Mahncke, H. W., & Zelinski, E. M. (2009). A cognitive training program based on principles of brain plasticity: Results from the improvement in memory with plasticity-based adaptive cognitive training (IMPACT) study. *Journal of the American Geriatrics Society*, *57*(4), 594–603. https://doi.org/10.1111/j.1532-5415.2008.02167.x

Spechler, P. A., Chaarani, B., Hudson, K. E., Potter, A., Foxe, J. J., & Garavan, H. (2016). Response inhibition and addiction medicine: From use to abstinence. In H. Ekhtiari & M. B. T.-P. in B. R. Paulus (Eds.), *Neuroscience for addiction medicine: From prevention to rehabilitation – Constructs and drugs* (vol. 223, pp. 143–164). Elsevier. https://doi.org/10.1016/bs.pbr.2015.07.024

Sterne, J. A. C., Savović, J., Page, M. J., Elbers, R. G., Blencowe, N. S., Boutron, I., Cates, C. J., Cheng, H.-Y., Corbett, M. S., Eldridge, S. M., Emberson, J. R., Hernán, M. A., Hopewell, S., Hróbjartsson, A., Junqueira, D. R., Jüni, P., Kirkham, J. J., Lasserson, T., Li, T., … Higgins, J. P. T. (2019). RoB 2: A revised tool for assessing risk of bias in randomised trials. *BMJ*, *366*, l4898. https://doi.org/10.1136/bmj.l4898

Stieger, M., & Lachman, M. E. (2021). Increases in cognitive activity reduce aging-related declines in executive functioning. *Frontiers in Psychiatry*, *12*, 708974. https://doi.org/10.3389/fpsyt.2021.708974

Takeda, S., & Fukuzaki, T. (2021). Development of a neuropsychological test to evaluate cognitive flexibility. *Yonago Acta Medica*, *64*(2), 162–167. https://doi.org/10.33160/yam.2021.05.003

Ten Brinke, L. F., Best, J. R., Chan, J. L. C., Ghag, C., Erickson, K. I., Handy, T. C., & Liu-Ambrose, T. (2020). The effects of computerized cognitive training with and without physical exercise on cognitive function in older adults: An 8-week randomized controlled trial. *The Journals of Gerontology*, *75*(4), 755–763. https://doi.org/10.1093/gerona/glz115

Traut, H. J., Guild, R. M., & Munakata, Y. (2021). Why does cognitive training yield inconsistent benefits? A meta-analysis of individual differences in baseline cognitive abilities and training outcomes. *Frontiers in Psychology*, *12*, 662139. https://doi.org/10.3389/fpsyg.2021.662139

Tripathi, R., Kumar, K., Bharath, S., M, P., Rawat, V. S., & Varghese, M. (2019). Indian older adults and the digit span A preliminary report. *Dementia & Neuropsychologia*, *13*(1), 111–115. https://doi.org/10.1590/1980-57642018dn13-010013

Turner, G. R., Novakovic-Agopian, T., Kornblith, E., Adnan, A., Madore, M., Chen, A. J. W., & D'Esposito, M. (2020). Goal-oriented attention self-regulation (GOALS) training in older adults. *Aging & Mental Health*, *24*(3), 464–473. https://doi.org/10.1080/13607863.2018.1534080

United Nations, Department of Economic and Social Affairs, Population Division. (2019). *World Population Prospects 2019: Highlights (ST/ESA/SER. A/423)*. New York, NY: United Nations. https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf.

*Van Het Reve, E., & De Bruin, E. D. (2014). Strength-balance supplemented with computerized cognitive training to improve dual task gait and divided attention in older adults: A multicenter randomized-controlled trial. *BMC Geriatrics*, *14*(1), 134. https://doi.org/10.1186/1471-2318-14-134

Wei, J., Hou, J., Mu, T., Sun, J., Li, S., Wu, H., Su, B., & Zhang, T. (2022). Evaluation of computerized cognitive training and cognitive and daily function in patients living with HIV: A meta-analysis. *JAMA Network Open*, *5*(3), e220970. https://doi.org/10.1001/jamanetworkopen.2022.0970

*Weicker, J., Hudl, N., Frisch, S., Lepsien, J., Mueller, K., Villringer, A., & Thöne-Otto, A. (2018). WOME: Theory-based working memory training – A placebo-controlled, double-blind evaluation in older adults. *Frontiers in Aging Neuroscience*, *10*(8), 247. https://doi.org/10.3389/fnagi.2018.00247

Wollesen, B., Wildbredt, A., van Schooten, K. S., Lim, M. L., & Delbaere, K. (2020). The effects of cognitive-motor training interventions on executive functions in older people: A systematic review and meta-analysis. *European Review of Aging and Physical Activity*, *17*(1), 9. https://doi.org/10.1186/s11556-020-00240-y

Weng, W., Liang, J., Xue, J., Zhu, T., Jiang, Y., Wang, J., & Chen, S. (2019). The transfer effects of cognitive training on working memory among chinese older adults with mild cognitive

impairment: A randomized controlled trial. *Frontiers in Aging Neuroscience*, *11*, 212. https://doi.org/10.3389/fnagi.2019.00212

Young, M. E., Sutherland, S. C., & McCoy, A. W. (2018). Optimal go/no-go ratios to maximize false alarms. *Behavior Research Methods*, *50*(3), 1020–1029. https://doi.org/10.3758/s13428-017-0923-5

Yun, S., & Ryu, S. (2022). The effects of cognitive-based interventions in older adults: A systematic review and meta-analysis. *Iranian Journal of Public Health*, *51*(1), 1–11. https://doi.org/10.18502/ijph.v51i1.8286