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Effectiveness of cognitive interventions in healthy aging: A systematic review and Bayesian meta-analysis

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ABSTRACT

The global increase of the aging population poses major public health challenges, particularly due to the rising prevalence of age-related diseases. Among these, dementia stands out as a condition with the most significant health, social, and economic impact. Primary prevention in healthy aging, thus far, represents the most effective strategy to address this issue, and cognitive interventions emerge as promising tools to enhance and preserve cognitive functions over time. This study aimed to provide a systematic review and meta-analysis of cognitive interventions in healthy older adults, assessing their effectiveness both on cognitive performance (i.e., global cognitive functioning and main cognitive domains), measured by neuropsychological tests, and psychological components (e.g., psychiatric symptoms, quality of life, reported cognitive complaints). The use of a multilevel Bayesian approach allowed us to enhance the reliability of our findings by accounting for data structure and variability across studies. A total of 51 studies were included in the systematic review, and 43 in the meta-analysis. The results indicated that, compared to control groups, cognitive interventions are more effective in improving overall cognition (0.26; 95 % CI [0.08, 0.44]). Evidence of effectiveness, albeit with smaller effect sizes, was also observed on specific cognitive domains. No effects emerged for psychological outcomes. Our findings underscore the relevance of cognitive interventions as an effective tool to promote cognitive health and prevent cognitive decline in the aging population. More research will be necessary to explore further the effectiveness of cognitive intervention on psychological components.

1. Introduction

Currently, almost all countries worldwide are experiencing a progressive aging of the population, characterized by increased life expectancy and declining fertility rates (Beard et al., 2016; Wang et al., 2020). While a longer lifespan is an important achievement, increased life expectancy does not necessarily correspond with healthy years (Choi et al., 2024). As people live longer, the prevalence of age-related diseases rises significantly; indeed, aging is the primary risk factor for many diseases and conditions that limit healthspan. This is especially true when it relates to cognitive decline, considering the growing number of elderly people living with a clinical diagnosis of dementia, particularly in low- and middle-income countries (Livingston et al., 2020; Livingston et al., 2024). Although dementia does not represent an inevitable consequence of aging (Qiu and Fratiglioni, 2018) and cognitive modifications in later life does not necessarily progress to a pathological condition, as sometimes occurs in case of Mild Cognitive Impairment (MCI; Petersen et al., 2018), such a syndrome stands out as one of the most impactful age-related diseases, as a major cause of disability and institutionalization in older people (Dartigues, 2009; Giaquinto et al., 2025; Mangialasche et al., 2012). It also represents a substantial challenge due to the considerable health, social, and economic burdens it imposes on

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individuals, families, and societies, as well as the strain it places on public healthcare systems and long-term care services (Aranda et al., 2021; Schaller et al., 2015).

While some approved drugs are emerging with encouraging results (Cummings and Fox, 2017; Smith and Ownby, 2024), widely accessible disease-modifying treatments are still needed (James and Bennett, 2019; Zagórska et al., 2023), and the costs of dementia care remain high.

Given these factors, primary prevention plays a critical role in improving quality of life during aging and unburdening healthcare systems (Nichols et al., 2022; Wu et al., 2023). According to Martins et al. (2018), primary prevention involves "action taken to avoid or remove the cause of a health problem in an individual or population before it arises." In the context of aging, primary prevention should first target healthy older individuals who may experience physiological cognitive decline that, even though quantitatively different from the pathological one, represents the typical phenotype resulting from modifications in specific cerebral areas with advancing age. Furthermore, subtle cognitive modifications (even subjective, as for subjective cognitive decline, SCD), which may predict future dementia, can appear several years before the disease fully meet the diagnostic criteria, suggesting that primary prevention should start as early as middle age (Petersen et al., 2018; Pike et al., 2022; Wang et al., 2021; Zhu et al., 2024). Overall, fostering such a preventive approach, minimizing modifiable risk factors and optimizing protective components for dementia among healthy individuals, could allow to promote a condition of active aging, especially thanks to the plasticity characterizing older adults' brain, still capable of responding to external stimulation.

As demonstrated by different environmental enrichment models (e.g., Hertzog et al., 2008; Leon and Woo, 2018), the role of social and cognitive engagement, along with a healthy lifestyle, appears to be crucial in preventive strategies (Grande et al., 2020; Pettigrew and Soldan, 2019). Based on the increasing interest in intellectually stimulating activities during aging, particularly for their implications in cognitive reserve (Daffner, 2010; Stern, 2009), a growing body of research recently focused on non-pharmacological cognitive interventions aimed at enhancing cognitive functions and preserving them over time.

In this regard, the umbrella term "cognitive interventions” concerns cognitive training and cognitive stimulation. Clare and Woods (2004), who were the first to systematically define these interventions, described cognitive training as guided practice on a set of standard tasks aimed at enhancing specific cognitive functions (e.g., memory, attention, language, or executive function). These interventions can be either multi-domain or uni-domain, delivered through individual or group sessions, using either paper-and-pencil or technology-based methods of administration. Cognitive training is usually structured across multiple levels of difficulty to tailor exercises to an individual's abilities. Additionally, Lustig et al., (2009) proposed a distinction among strategic, multimodal, and process-based cognitive training approaches. On the other hand, cognitive stimulation interventions imply “the engagement in a range of group activities and discussions (usually in a group) aimed at general enhancement of cognitive and social functioning” (Clare and Woods, 2004). Rather than focusing only on cognition, these interventions would be beneficial because they address under-functioning aspects that result from insufficiently stimulating and rewarding social environments, making this type of intervention suitable also to individuals with MCI and in an early stage of dementia (e.g., Aguirre et al., 2013).

Previous studies have conducted systematic reviews and meta-analyses on cognitive interventions in healthy older adults and in individuals in midlife, demonstrating their effectiveness (e.g., Chiu et al., 2017; Gómez-Soria et al., 2023; Lampit et al., 2014; Martin et al., 2011; Mowszowski et al., 2016; Nguyen et al., 2019; Papp et al., 2009; Zehnder et al., 2009; Zhu et al., 2024). However, many of these works have focused on evaluating the effectiveness of a single type of interventions (e.g., cognitive training or cognitive stimulation alone, interventions targeting a single cognitive component, or exclusively computerized interventions). Additionally, several studies have not clearly distinguished between cognitive training, cognitive stimulation, and rehabilitation (i.e., personalized intervention to improve daily functioning in individuals with specific illness or injury-related impairments; Clare and Woods, 2004), or have included clinical populations (e.g., patients with dementia) beyond healthy elderly individuals. Only one study (Kelly et al., 2014) investigated the impact of cognitive interventions on specific cognitive domains and daily functioning, clearly distinguishing between cognitive training and stimulation, and involving exclusively healthy older adults. Results from this work demonstrated that cognitive training positively impacts executive functions and global cognitive performance when compared to active control groups. It also improves memory and subjective cognitive functioning, compared to no intervention. On the other hand, further research appeared to be necessary to evaluate the potential benefits of general mental stimulation on cognitive functions. The absence of everyday functioning measures in most studies limited the conclusions about the effectiveness of cognitive interventions in daily life.

For this reason, our study aimed to carry out a systematic review of the current literature on cognitive interventions in healthy older adults, quantifying their effectiveness on cognitive functioning. Specifically, we evaluated the impact of the treatment on cognitive performance, as measured by neuropsychological tests, and psychological aspects, including psychiatric symptoms, functionality of daily living, and quality of life, assessed through specific questionnaires.

In this study we adopted a multilevel Bayesian metanalysis approach, which has several advantages (Garrett et al., 2024; Reis et al., 2023): it allows for the incorporation of prior expectation into the analysis, offers a clearer identification of heterogeneity sources and enhances the precision of pooled effect size estimates, also in the case of a small number of studies.

2. Materials and methods

2.1. Identification of studies

Our systematic review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) and its protocol has been registered in the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number CRD42023421720 (https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42023421720).

On May 18, 2023, a comprehensive search was performed by two authors (SP, GT) across three databases (Scopus, Web of Science, and PubMed) using the following search string: ((cognitive training*) OR (cognitive based training*) OR (strategy training*) OR (strategic training*) OR (process training*) OR (cognitive stimulation*) OR (cognitive based stimulation*) OR (cognitive intervention*) OR (cognitive based intervention*) OR (brain training) OR (cognitive program*) OR (cognitive based program*) OR (cognitive potentiation) OR (brain potentiation) OR (cognitive rehabilitation*)) AND ((healthy adult*) OR (healthy older*) OR (healthy elder*) OR (healthy aging) OR (healthy ageing)) AND ((cogniti* assessment) OR (neuropsycholog* assessment) OR (neuropsycholog* evaluation) OR (cogniti* evaluation) OR (cogniti* test*)).

Screening was conducted using Rayyan software (https://rayyan.qcri.org/welcome; Ouzzani et al., 2016). Duplicate papers were removed, and then three members of the research group (SP, MD, FC) independently screened the titles and abstracts of all retrieved articles. Each record was randomly assigned to two raters in order to exclude off-topic and inappropriate papers. In cases of disagreement, a third researcher (GT) was consulted. As a second step, four members of the research group (LV, SP, MD, FC) collected all selected studies and independently evaluated them for eligibility by consulting the full text.

2.2. Study selection

The meta-analysis included randomized controlled trials (RCT) and non-randomized pre-post intervention studies with control groups published in English in peer-reviewed journals. Eligibility criteria were defined following the PICOS framework, including Population, Intervention, Comparison Intervention, and Outcome(s). Based on this framework, we decided to consider only the studies that fulfilled the following inclusion criteria: (1) articles including adults individuals older than 60 years old, with a mean age higher than 65, without cognitive deficits or impairments, neurological or psychiatric history (e.g., Mild Cognitive Impairment (MCI), stroke, traumatic brain injury, dementia); (2) intervention studies containing cognitive training or cognitive stimulation, according to Clare and Woods (2004)'s definitions, and (3) an active (e.g., alternative activities), non-active (e.g., waiting list), or no-treatment control group; (4) articles including assessment of cognitive functioning through neuropsychological tests. In this regard, as the main outcome, we considered general cognitive status, assessed by a screening test (e.g., MoCA, MMSE, RBANS). As additional outcomes, we included specific cognitive domain performances (e.g., Trail Making Test, Stroop Test, Rey Auditory Verbal Learning Test, Digit Span Forward and Backward, Digit Symbol Test), biomarkers (e.g., neurophysiological measures), and psychological measures (e.g., psychiatric symptoms, reported complaints, daily living functionality, quality of life).

2.3. Data extraction

Each eligible full-text article was independently analyzed by two reviewers of the authors' team (SP and LV). For studies characterisation,

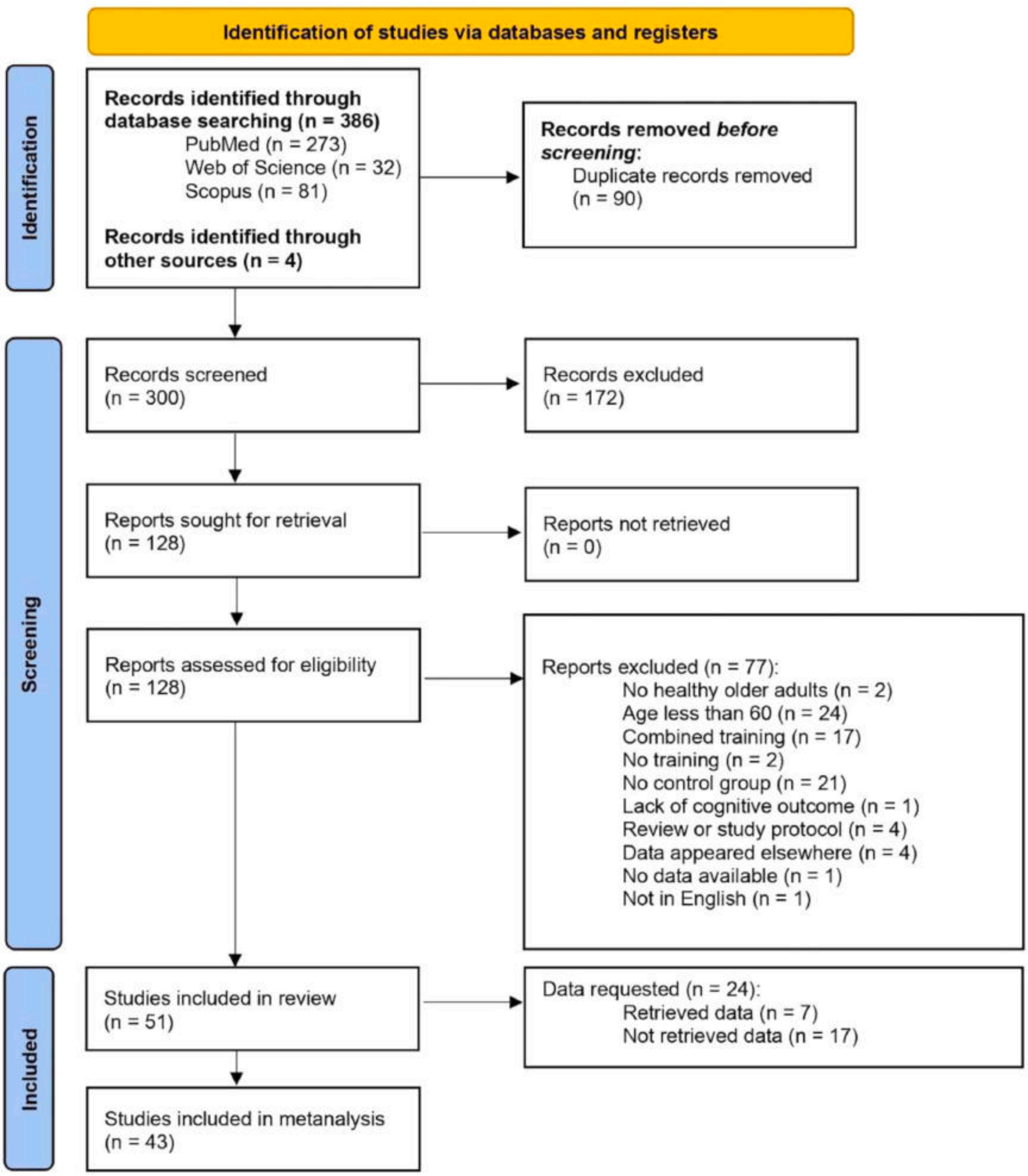

Fig. 1. *PRISMA flow diagram.* PRISMA flow diagram summarizing search, screening and selection procedure for the review (Page et al., 2021).

the authors extracted the following information: type of intervention (cognitive training or cognitive stimulation), format (group or individual), method of administration (technology-based, paper-and-pencil), duration, follow-up (presence and timing), training modality (face-to-face or at distance), outcome (cognitive assessment, biomarker, psychological questionnaires), trained domain (multi- or uni-), and population (community-dwelling, long-term care facilities). For the effect size estimation, we extracted scores from neuropsychological tests, biomarkers, psychological and functional questionnaires (if present). In particular, sample size, means, and standard deviations, before and after the cognitive intervention were extracted for the experimental and control group. When reported, we also extracted the effect size for each test related to the difference between pre- and post-cognitive assessment for both the experimental and the control group.

In case of multiple control groups in the same study, the most active one (i.e., alternative activities over waiting list and no-treatment control group) was selected, provided they did not involve other cognitive interventions. In the absence of other control groups, physical activity groups were also considered as active control groups. The rationale for adopting this more conservative strategy lies in the fact that, when an active control group is used, effects resulting from the comparison with cognitive interventions may lead to smaller, but also more valid and stronger results than those obtained, for instance, when compared with a no-treatment control group. Indeed, in experimental groups and in active control groups, a certain effect is expected in both cases, despite being smaller in the latter.

In case of more than one follow-up, the first post-intervention assessment was considered. When the raw test scores were not available for the experimental group and/or for the control group, we reached out to the corresponding author for missing data. 24 authors were contacted for additional information regarding as many papers. The paper was excluded after three attempts with no response. Among the authors contacted, 11 authors responded, and 7 provided numerical data. A PRISMA Flow Diagram (Page et al., 2021) is shown in Fig. 1 to illustrate the search procedure.

2.4. Assessment of methodological quality

The Risk of Bias In Non-randomized Studies - of Interventions tool (ROBINS-I; Sterne et al., 2016) was used to assess the methodological quality of papers. The risk of bias assessment was conducted by two authors of the present work (FF and LV). The ROBINS-I examines risk bias across seven domains: (1) bias due to confounding; (2) bias in participant selection; (3) bias in intervention classification; (4) bias due to intervention deviation; (5) bias due to missing data; (6) bias in outcomes measurement; (7) bias in selection of reported results (Sterne et al., 2016).

Each study was rated as having a low risk (comparable to a well-conducted randomized control trial), moderate risk (a well-performed non-randomized study), serious risk (presence of important problems), or critical risk (too problematic to provide evidence). The overall bias risk was determined by the highest level of risk identified across all domains.

2.5. Data synthesis and analysis

All the analyses were performed using the statistical environment R (R Core Team, 2023). To obtain the effect size in order to assess the effectiveness of cognitive intervention, we referred to Morris (2008) (p. 369). The paper specifically focuses on the pretest-posttest-control (PPC) design, which controls for preexisting differences, allowing estimates of treatment effectiveness even when treatment and control groups are nonequivalent (Cook and Campbell, 1979; Morris and DeShon, 2002). The author compared three alternative effect size estimates in terms of bias, precision, and robustness to heterogeneity of variance and favored an effect size based on the mean pre-post change in the treatment group minus the mean pre-post change in the control group, divided by the pooled pretest standard deviation (d_{ppc2}). This index is based on the classical standardized mean difference (post-pre) divided by the standard deviation of the pre-test score, which is less likely to be influenced by the intervention effect (Becker, 1988). Morris suggested standardizing the mean difference using the pooled pretest standard deviation to meet the assumption that the population variances are homogeneous. The formula also includes a function (c_p), indicating the degree of bias depending on the sample sizes.

Effect sizes were calculated with ad-hoc formulas and reversed in the case of outcomes assessing errors or execution time, thus standardising the interpretation (i.e., the higher the score, the better the performance). Effect sizes are reported in the Supplementary Materials (Table1).

The effect sizes for cognitive screening tests were considered the primary outcome. All other neuropsychological tests have been classified into broad abilities domains through Cattel-Horn-Carroll-Miyake (CHC-M) taxonomy (Webb et al., 2018), including fluid reasoning, long-term memory storage and retrieval, general short-term memory, executive functions, processing speed, and visual processing. Specific tests included in each domain are reported in the Supplementary Materials (Table1). Consistently with the other types of outcomes extracted from the articles, we also added the following domains: reported cognitive complaints, cognitive self-awareness, functional capacity (i.e., autonomy), psychiatric symptoms and quality of life. For each broad cognitive ability, we performed a frequentist random-effects metanalysis (by using the R function "metagen" in the "meta" package). Fitting a frequentist meta-analysis allowed us to identify outliers (by using the R function "find.outliers" in the "dmetar"package) and influential points (by using the R function "InfluenceAnalysis" in the "dmetar" package). Indeed, in the case of studies with extreme effect sizes (i.e., the effect size confidence interval does not overlap with the pooled effect confidence interval), the pooled effect estimate may be distorted, influencing heterogeneity between studies. As a result, any studies with extreme effect sizes were excluded from the analysis, leading to an updated evaluation of the pooled effect estimate. On the other hand, influential points were studies that considerably impacted the pooled effect size calculation. We decided to acknowledge them rather than exclude them from the analysis. Potential publication bias was assessed through either a funnel plot and Egger's test (by using the "funnel" and "metabias" functions from the "meta" package).

Most of the included studies reported multiple outcomes, covering more than one cognitive domain and more than one test in each domain. However, extracting many effect sizes from a single study would lead to a violation of the meta-analysis assumption of independence (Lortie, 2022; Van Den Noortgate et al., 2015). Effect sizes within the same study were extracted from the same sample; thus, being more similar than effect sizes from different studies. If there is a dependency between effect sizes (i.e., effect sizes are correlated), this can artificially reduce heterogeneity and thus lead to false-positive results (unit-of-analysis error). Hence, when necessary, we applied a multilevel approach to the current meta-analysis to account for the dependency of effect sizes. In particular, we adopted a three-level meta-analysis model, where the first level represented single study aggregated effect size; in the second level, effects sizes based on different cognitive tests were nested within studies; and the third level consisted of the pooled effect size. The multilevel Bayesian random-effect meta-analysis was performed using the R function "brm" in the "brms" package. We calculated the pooled effect size and the heterogeneity between studies and outcomes. The estimation started from a non-informative prior with a normal distribution (mean = 0, scale = 10) for the effect size and a half-Cauchy distribution (mean = 0, scale = 0.5) for the heterogeneity. We also conducted posterior predictive checks to assess the model convergence and the overall validity of the results using the R function "pp_check" in the "brms" package. In order to evaluate how the quality of the studies included in the meta-analysis could impact the results and their reliability, we also performed the same analyses excluding outcomes from works with severe or critical level of risk of bias, only taking into account those with a lower level of risk (as assessed by the ROBINS-I tool; Sterne et al., 2016).

Data and analysis code are available on the Open Science Framework platform at the following

link: https://osf.io/a586p/?view_only=bafc6ba2db574d66acc1368c2e591459

3. Results

3.1. Search results

The systematic search yielded 390 results, which decreased to 300 after removing duplicates. After assessing titles and abstracts for eligibility, as well as the conflict resolution, 172 articles were excluded. Full versions were obtained for 128 articles, of which 51 met the criteria for inclusion in the review. 43 studies reported all the information needed for the analysis and were included in the meta-analysis (see Fig. 1 for detailed search results).

3.2. Characteristics of included studies

Overall, 3290 healthy elderly individuals, older than 60, were included in our review. Across 51 studies included, the assessed population comprised community-dwelling older adults, with only one exception (i.e., Estrada-Plana et al., (2021), in which participants were recruited from long-term care facilities (See Fig. 2 for a summary of the findings from the review).

The most common intervention was cognitive training (94 %); in only 3 studies (i.e., Estrada-Plana et al., 2021; MacRitchie et al., 2020; Tranter and Koutstaal, 2008) the intervention consisted of cognitive stimulation. These articles were nevertheless included in the study, as both cognitive training and stimulation could be considered as cognitive interventions (Clare and Woods, 2004).

Globally, the cognitive interventions were administered more in a group format than in an individual one (43 % and 37 %, respectively), with only a case being mixed (i.e., Tranter, Koutstaal, 2008). In 9 studies (18 %), the format was not clearly specified.

The method of administration was mostly technology-based (65 %), while the paper-and-pencil approach was used relatively infrequently (6 %). In two cases, the administration method was mixed, meaning

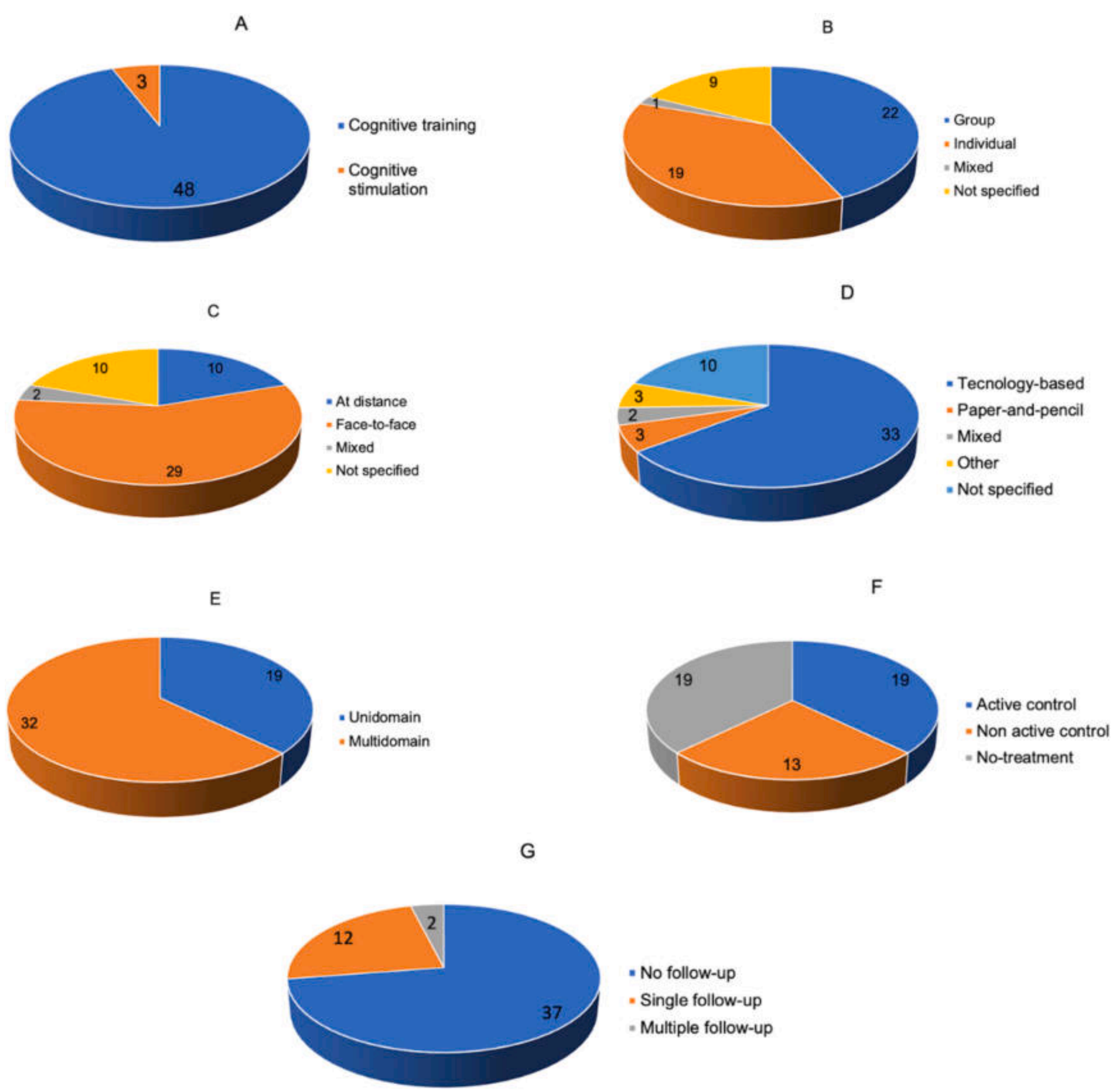

Fig. 2. *Graphical summary of review results.* Summary of the main findings from the reviewed studies (A Cognitive Intervention; B Format; C Modality of Administration; D Method of Administration; E Domain; F Control group; G Follow-up).

they included both technology-based and paper-and-pencil exercises (i.e., Gajewski, Falkenstein, 2018; Gajewski et al., 2020). In 3 studies (i.e., Estrada-Plana et al., 2021; Kuo et al., 2018; MacRitchie et al., 2020), the method of administration could not be classified among the previous categories (e.g., music-making, decks of cards, etc.). In 10 cases (19 %), the method of administration was not clearly specified.

As for the modality of administration, we observed that face-to-face was used in the majority of cases (56 %), while the "at distance" type was used in only ten studies (20 %). Two studies employed a mixed modality of administration, both face-to-face and remote (i.e., Shatil et al., 2014; Tranter and Koutstaal, 2008). In 10 cases (20 %), the modality of administration was not clearly specified.

The cognitive intervention was multidomain in 32 studies (63 %), while in 19 studies it was unidomain (37 %), most often with a specific focus on executive functions.

Regarding the type of control group used, the active and no-treatment groups were employed equally across the studies (37 % each). Physical activity was the most common type of active control group (47 %). We found the use of non-active control groups (i.e., waiting-list) in 13 articles (26 %).

Additional follow-up assessments, after the post-intervention one, were present in 14 studies (27 %); in 12 of them (23 %), there was a single follow-up (range: 3–12 months; mean interval: 5.2 ± 3.4 months); in 2 cases (i.e., Baltes et al., 1986; Cheng et al., 2012), multiple follow-ups were conducted (range: 1–12 months; mean interval: 6.3 ± 4.5 months).

Concerning the organization of cognitive interventions, the total number of sessions varied considerably across studies (range: 5–50; mean and standard deviation: 28.2 ± 12.1). In only one case, the number of sessions was not specified (i.e., da Mota Antunes et al., 2023). The frequency of sessions was three times a week in most cases (39 %); in 5 studies (10 %), it was not specified. The mean duration of a single session was about one hour (range: 6–120 min; mean duration and standard deviation: 56.2 ± 24.7

About the outcomes, cognitive assessment was included in 50 articles, except for one work (da Mota Antunes et al., 2023), which contained only psychiatric and reported cognitive complaints indicators. Thirteen (25 %) studies included neurophysiological data (i.e., RS-fRMI, EEG, ERP, fMRI, DTI, PET, measures of BDNF and platelet PLA_2), 7 (14 %) studies included measurements of reported memory complaints and 6 (12 %) psychiatric outcomes (depression and anxiety symptoms, in particular). Quality of life indicators were contained in only four articles (i.e., Almondes et al., 2017; Estrada-Plana et al., 2021; Shah et al., 2014; Shatil et al., 2014), while functional capacity and self-awareness components were present each in one work (i.e., respectively Shatil et al., 2013; Srisuwan, 2020). See Table 1 for a detailed description of studies' characteristics.

3.3. Efficacy in global cognitive functioning

A total of 476 experimental subjects and 480 control participants from 13 studies were included in the meta-analysis about the efficacy of cognitive intervention on global cognitive functioning (as assessed by screening tests). The analysis revealed the presence of an influential point (Millán-Calenti et al., 2015) and no outliers. There was no need to use a multilevel model since only one outcome was included in each study. The overall weighted effect size was 0.26 (95 % CI [0.08, 0.44]), meaning that the cognitive intervention is moderately more effective on global cognitive functioning than the activities performed by the control groups. Regarding heterogeneity, tau was 0.14 (95 % CI [0.01, 0.38]), suggesting a low level of between-study variability, as tau values closer to zero indicate less heterogeneity (Ariel De Lima et al., 2022). Fig. 3 shows the forest plot. Results from the linear regression test of the funnel plot (Egger's test) indicated that the data included are symmetric (bias = 0.61; se = 0.88; t (11) = 0.70, p = 0.49), suggesting no evidence of publication bias. Posterior Predictive Check results are reported in the Supplementary Materials.

In the analysis that took into account only studies without a severe or critical level of risk of bias, the overall weighted effect size was 0.20 (95 % CI [0.01, 0.39]) and, concerning the heterogeneity, tau was 0.12 (95 % [0.01, 0.38]); the complete results (outliers, points of influence, forest plot, posterior predictive check) are reported in the Supplementary Materials.

3.4. Domain-specific efficacy

3.4.1. Fluid reasoning

A total of 617 experimental subjects and 618 control participants from 32 outcomes in 18 studies were included in the meta-analysis about the efficacy of cognitive interventions on fluid reasoning. An outcome from the study by Van Muijden et al. (2012) was excluded from the original set of fluid reasoning outcomes due to being an outlier. The analysis revealed no influential points. The overall weighted effect size was 0.16 (95 % CI [0.02, 0.29]), suggesting the effectiveness of the cognitive interventions against the control group activities in this domain, although the effect size is small. Heterogeneity across studies was tau = 0.11 (95 % CI [0.01, 0.28]); heterogeneity across outcomes was tau = 0.20 (95 % CI [0.07, 0.33]). Fig. 4 shows the forest plot with outcomes aggregated within studies. Results from the linear regression test of the funnel plot indicated that the data included are symmetric (bias = −0.51; se = 0.82; t (30) = -0.62, p = 0.54), suggesting no evidence of publication bias. Posterior Predictive Check results are reported in the Supplementary Materials. In the analysis that included only studies without a severe or critical level of risk of bias, the overall weighted effect size was 0.11 (95 % CI [-0.03, 0.26]). Heterogeneity across studies was tau = 0.12 (95 % [0.01, 0.30]); heterogeneity across outcomes was tau = 0.10 (95 % [0.00, 0.26]). The complete results (outliers, points of influence, forest plot, posterior predictive check) are reported in the Supplementary Materials.

3.4.2. Long-term memory storage and retrieval

A total of 975 experimental subjects and 954 control participants from 78 outcomes and 30 studies were included in the meta-analysis on long-term memory storage and retrieval. The analysis revealed the presence of four influential points from one study (Yeo et al., 2018) and no outliers. The overall weighted effect size was 0.16 (95 % CI [0.09, 0.22]), which is considered small. It indicated the effectiveness of the cognitive interventions against the control group activities in long-term memory storage and retrieval. Heterogeneity across studies was tau = 0.05 (95 % CI [0.00, 0.14]); heterogeneity across outcomes was tau = 0.04 (95 % CI [0.00, 0.10]). Fig. 5 shows the forest plot with outcomes aggregated within studies. Results from the linear regression test of the funnel plot indicated that the data included are asymmetric (bias = 0.58; se = 0.27; t (76) = 2.17, p = 0.03), suggesting the potential presence of publication bias. Posterior Predictive Check results are reported in the Supplementary Materials. In the analysis that considered only studies without a severe or critical level of risk of bias, the overall weighted effect size was 0.15 (95 % CI [0.08, 0.24]). Heterogeneity across studies was tau = 0.07 (95 % [0.00, 0.19]); heterogeneity across outcomes was tau = 0.04 (95 % [0.00, 0.12]). The complete results (outliers, points of influence, forest plot, posterior predictive check) are reported in the Supplementary Materials.

3.4.3. General short-term memory

A total of 718 experimental subjects and 618 control participants from 62 outcomes and 23 studies were included in the meta-analysis about the efficacy of cognitive interventions on general short-term memory, which includes memory span and working memory. The analysis revealed the presence of six extreme outcomes (i.e., Nozawa et al., 2015, Sandberg et al., 2014, Weicker et al., 2018), of which three from one study (i.e., Shatil et al., 2014), removed from the original set of outcomes, due to being outliers. No influential points were detected. The

Table 1
Characteristics of studies included in the review.

Intervention													Control	
Study	Cognitive intervention	Format	Administration	Total duration	Session duration	Frequency	Follow-up	Timing of the follow-up	Modality	Outcome	Domain	Population	Control type	Control group activity
Almondes et al., (2017)	Cognitive Training	Not specified, probably in group	Not specified, probably paper-and-pencil	6	90	Not specified	No		Not specified, probably face-to-face	Cognitive assessment, QoL (sleep measures)	Multidomain	Community-dwelling	Active	Sleep Hygiene (i.e., behavioral and environmental recommendations to promote healthy sleep through the gradual restructuring of poor habits in relation to sleep)
Baltes et al., (1986)	Cognitive Training	Group	Not specified	10	60	Not specified	Yes (multiple follow-up)	1 month; 6 months	Face-to-face	Cognitive assessment	Unidomain	Community-dwelling	No treatment	None
Baltes et al., (1989)	Cognitive Training	Group	Paper-and-pencil	5	60	Not specified	No		Face-to-face	Cognitive assessment	Unidomain	Community-dwelling	No treatment	None
Barban et al., (2016)	Cognitive Training	Group	Technology-based	24	60	2 s/w	Yes (single follow-up)	3 months	Not specified, probably face-to-face	Cognitive assessment	Multidomain	Community-dwelling	Non-active	Waiting-list control group
Barban et al., (2017)	Cognitive Training	Individual	Technology-based	24	60	2 s/w	Yes (single follow-up)	6 months	Not specified	Cognitive assessment, neurophysiological (RS-fMRI)	Multidomain	Community-dwelling	Active control	Entering lists of Italian names and numeric values taken from an Italian lexicon
Binder et al., 2016	Cognitive Training	Individual	Technology-based	50	45/60	5 s/w	Yes (single follow-up)	6 months	At distance	Cognitive assessment	Multidomain	Community-dwelling	No treatment	None
Cheng et al., 2012	Cognitive Training	Group	Not specified, probably paper-and-pencil	24	60	2 s/w	Yes (multiple follow-up)	6 months; 12 months (post-booster)	Face-to-face	Cognitive assessment	Unidomain	Community-dwelling	Non-active	Waiting-list control group
Constantinidou, (2019)	Cognitive Training	Individual	Not specified, probably paper-and-pencil	27 (on average)	60	2–4 s/w	No		Face-to-face	Cognitive assessment	Multidomain	Community-dwelling	No treatment	None
Downey et al., (2022)	Cognitive Training	Group	Technology-based	36	60	3 s/w	No		Face-to-face	Cognitive assessment	Unidomain	Community-dwelling	Active	Physical activity
Estrada-Plana et al., (2021) pilot	Cognitive Stimulation	Group	Board and card games	10	90	2 s/w	No		Face-to-face	Cognitive assessment, psychiatric (depression), QoL	Multidomain	Long-term care facilities	Non-active	Waiting-list control group
Faraza et al., (2021)	Cognitive Training	Not specified	Technology-based	12	90	3 s/w	Yes (single follow-up)	3 months (12 weeks)	Not specified, probably face-to-face	Cognitive assessment, neurophysiological (RS-fMRI)	Multidomain	Community-dwelling	No treatment	None
Faust et al., (2020)	Cognitive Training	Individual	Technology-based	30–40	30/40	Not specified	No		At distance	Cognitive assessment	Multidomain	Community-dwelling	Non-active	Waiting-list control group
Faust et al., (2020) pilot	Cognitive Training	Individual	Technology-based	30–40	30/40	Not specified	No		At distance	Cognitive assessment	Multidomain	Community-dwelling	Non-active	Waiting-list control group

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Table 1 (*continued*)

Intervention													Control	
Study	Cognitive intervention	Format	Administration	Total duration	Session duration	Frequency	Follow-up	Timing of the follow-up	Modality	Outcome	Domain	Population	Control type	Control group activity
Gajewski, Falkenstein, (2018)	Cognitive Training	Group	Mixed	32	90	2 s/w	No		Face-to-face	Cognitive assessment, neurophysiological (ERP)	Multidomain	Community-dwelling	Active	Physical activity
Gajewski et al., (2020)	Cognitive Training	Group	Mixed	32	90	2 s/w	No		Face-to-face	Cognitive assessment, functional capacity	Multidomain	Community-dwelling	Active	Physical activity
Goghari, Lawlor-Savage, (2017)	Cognitive Training	Individual	Technology-based	40	30	5 s/w	No		At distance	Cognitive assessment	Unidomain	Community-dwelling	No treatment	None
Golino et al., (2017)	Cognitive Training	Individual	Not specified, probably paper-and-pencil	12	60/90	1 s/w	No		Not specified, probably face-to-face	Cognitive assessment	Multidomain	Community-dwelling	Non-active	Waiting-list control group
Grönholm-Nyman et al., (2017)	Cognitive Training	Group (individually, when needed)	Technology-based	15	45/60	3 s/w	Yes (single follow-up)	12 months	Face-to-face	Cognitive assessment	Unidomain	Community-dwelling	Active	Participants played three different computer games
Gu et al., 2021	Cognitive Training	Not specified, probably in group	Not specified, probably paper-and-pencil	24	60	2 s/w	No		Face-to-face	Cognitive assessment, neurophysiological (RS-fMRI)	Multidomain	Community-dwelling	No treatment	None
Jaeggi et al., 2020	Cognitive training	Individual	Technology-based	20	Not specified	2 s/d; 1 s/d; 1 s/every-other-day	Yes (single follow-up)	3 months	At distance	Cognitive assessment	Unidomain	Community-dwelling	Active	Knowledge skills training
Ji et al., (2020)	Cognitive Training	Group	Not specified	36	60	3 s/w	No		Not specified, probably face-to-face	Cognitive assessment	Multidomain	Community-dwelling	Active	Physical activity
Kim et al., (2017)	Cognitive Training	Not specified	Technology-based	24	60	3 s/w	No		Face-to-face	Cognitive assessment, neurophysiological (fMRI)	Unidomain	Community-dwelling	No treatment	None
Kinsella et al., (2015)	Cognitive Training	Group	Not specified, probably mixed	6	120	1 s/w	Yes (single follow-up)	6 months	Face-to-face	Cognitive assessment, reported cognitive complaints	Unidomain	Community-dwelling	Non-active	Waiting-list control group
Kuo et al., 2018	Cognitive Training	Group	Decks of cards	16	75	2 s/w	No		Face-to-face	Cognitive assessment	Multidomain	Community-dwelling	Active	Commercial board games
Lampit et al., 2015	Cognitive Training	Group	Technology-based	36	60	3 s/w	Yes (single follow-up)	3 months	Face-to-face	Cognitive assessment, neurophysiological (s-MRI; RS-fMRI; 1H-MRS; metabolites, DTI)	Multidomain	Community-dwelling	Active	Participants watched seven short National Geographic videos per session on a computer and answered multiple-choice questions immediately after each presentation.
Lee et al., (2013)	Cognitive Training	Individual	Technology-based	24	30	3 s/w	No		Not specified	Cognitive assessment	Unidomain	Community-dwelling	Non-active	Waiting-list control group
Lee et al., (2024)	Cognitive Training	Individual	Technology-based	24	30	3 s/w	No		Not specified	Cognitive assessment	Unidomain	Community-dwelling	Non-active	Waiting-list control group
MacRitchie et al., 2020	Cognitive Stimulation	Group	Music-making	10	60	1 s/w	No		Face-to-face	Cognitive assessment	Multidomain	Community-dwelling	Non-active	Waiting-list control group

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Table 1 (*continued*)

Intervention													Control	
Study	Cognitive intervention	Format	Administration	Total duration	Session duration	Frequency	Follow-up	Timing of the follow-up	Modality	Outcome	Domain	Population	Control type	Control group activity
Marusic et al., (2022)	Cognitive Training	Group	Technology-based	48	40	3 s/w	No		Face-to-face	Cognitive assessment, neurophysiological (ERP)	Multidomain	Community-dwelling	Non-active	Waiting-list control group
Millán-Calenti et al., (2015)	Cognitive Training	Individual	Technology-based	24	20	2 s/w	No		Not specified, probably face-to-face	Cognitive assessment, psychiatric	Multidomain	Community-dwelling	No treatment	None
Miller et al., (2012)	Cognitive Training	Group	Not specified, probably paper-and-pencil	12	60	2 s/w	No		Face-to-face	Cognitive assessment, reported cognitive complaints	Unidomain	Community-dwelling	Non-active	Waiting-list control group
Nicastri et al., (2022)	Cognitive Training	Individual	Technology-based	25	40	5 s/w	No		At distance	Cognitive assessment, neurophysiological (BDNF)	Multidomain	Community-dwelling	Active	Physical activity
Niu et al., 2016	Cognitive Training	Not specified, probably in group	Technology-based	16	60	3 s/w	No		Face-to-face	Cognitive assessment, neurophysiological (ERP)	Multidomain	Community-dwelling	No treatment	None
Nozawa et al., 2015	Cognitive Training	Individual	Technology-based	24	20	3 s/w	No		Face-to-face	Cognitive assessment, neurophysiological (MRI, MEG)	Multidomain	Community-dwelling	Active	Crossword puzzles
Pothier et al., 2021	Cognitive Training	Not specified	Technology-based	36	60	3 s/w	No		Face-to-face	Cognitive assessment	Unidomain	Community-dwelling	Active	Physical activity
Raichlen et al., (2020)	Cognitive Training	Not specified, probably in group	Technology-based	36	30	3 s/w	No		Face-to-face	Cognitive assessment	Multidomain	Community-dwelling	Active	Physical activity
Sandberg et al., 2014	Cognitive Training	Group	Technology-based	15	45	3 s/w	No		Face-to-face	Cognitive assessment, reported cognitive complaints	Unidomain	Community-dwelling	No treatment	None
Shah et al., 2014	Cognitive Training	Individual	Technology-based	40	60	5 s/w	No		At distance	Cognitive assessment, QoL, reported cognitive complaints, psychiatric, neurophysiological (PET)	Multidomain	Community-dwelling	Active	Physical activity
Shatil, (2013)	Cognitive Training	Group	Technology-based	48	40	3 s/w	No		Face-to-face	Cognitive assessment, self awareness	Multidomain	Community-dwelling	Active	Physical activity
Shatil et al., 2014	Cognitive Training	Not specified, probably individual	Technology-based	24	20	3 s/w	No		Mixed (at distance and face-to-face)	Cognitive assessment, QoL	Multidomain	Community-dwelling	Active	Engagement in non-cognitive activities (e.g., composing family stories using memories of life milestones…)
Srisuwan et al., 2020	Cognitive Training	Group	Paper-and-pencil	5	120	2 s/m	Yes (single follow-up)	12 months	Face-to-face	Cognitive assessment, psychiatric (anxiety and depression), functional capacity	Multidomain	Community-dwelling	No treatment	None (standard clinical care)
Studer-Luethi et al., (2023)	Cognitive Training	Individual	Technology-based	20	20	5 s/w	No		At distance	Cognitive assessment, reported cognitive complaints	Unidomain	Community-dwelling	No treatment	None
Sutter et al., 2013	Cognitive Training	Individual	Telephone-based	15	6	5 s/w	No		At distance	Cognitive assessment, psychiatric (depression and anxiety)	Unidomain	Community-dwelling	Active	Participants were asked about their opinion, thoughts and experiences on a given

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Table 1 (*continued*)

Intervention													Control	
Study	Cognitive intervention	Format	Administration	Total duration	Session duration	Frequency	Follow-up	Timing of the follow-up	Modality	Outcome	Domain	Population	Control type	Control group activity
														topic (e.g., 'movies' or 'traveling').
Tagliabue et al., (2018)	Cognitive Training	Group	Technology-based	13	60	1 s/w	No		Face-to-face	Cognitive assessment	Multidomain	Community-dwelling	No treatment	None
Talib et al., 2008	Cognitive Training	Group	Paper-and-pencil	4	90	2 s/w	No		Face-to-face	Cognitive assessment, neurophysiological (platelet PLA_2)	Multidomain	Community-dwelling	No treatment	None (standard outpatient care)
Tranter, Koutstaal, (2008)	Cognitive Stimulation	Mixed (individual and in group)	Not specified, probably paper-and-pencil	15	40/60	2 s/w	No		Mixed (at distance and face-to-face)	Cognitive assessment	Multidomain	Community-dwelling	No treatment	None
Van Muijden et al., (2012)	Cognitive Training	Individual	Technology-based	49	30	Everyday	No		At distance	Cognitive assessment	Multidomain	Community-dwelling	Active	Participants answered quiz questions about documentaries online
da Mota Antunes et al., 2023	Cognitive Training	Individual	Technology-based	Not well specified (duration: 12 weeks)	90	1 s/w	No		At distance	Reported cognitive complaints, psychiatric (depression and anxiety)	Multidomain	Community-dwelling	Non-active	Waiting-list control group
Weicker et al., 2018	Cognitive Training	Group	Technology-based	12	45	3 s/w	Yes (single follow-up)	3 months	Face-to-face	Cognitive assessment, reported memory complaints	Unidomain	Community-dwelling	No treatment	None
Wiśniowska, 2022	Cognitive Training	Individual	Technology-based	12	30	3 s/w	No		Face-to-face	Cognitive assessment	Unidomain	Community-dwelling	No treatment	None
Wolf et al., (2014)	Cognitive Training	Not specified	Technology-based	11	60	3 s/w	Yes (single follow-up)	3 months	Not specified, probably face-to-face	Cognitive assessment, neurophysiological (DTI)	Unidomain	Community-dwelling	No treatment	None
Yeo et al., 2018	Cognitive Training	Individual	Technology-based	27	40	3 s/w	Yes (single follow-up)	3 months (12 weeks)	Face-to-face	Cognitive assessment	Multidomain	Community-dwelling	Non-active	Waiting-list control group

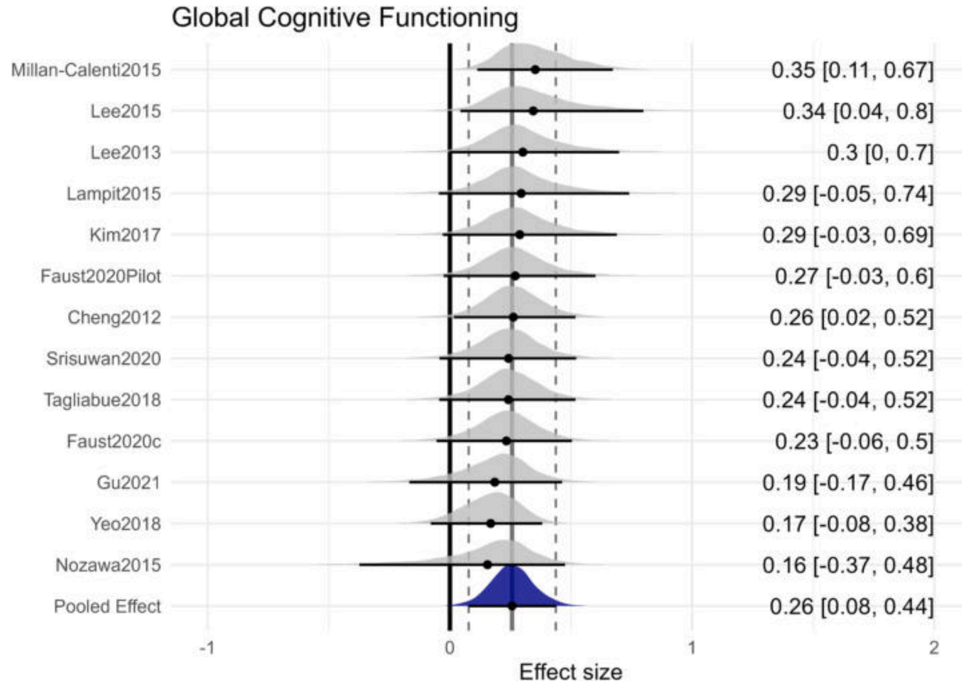

Fig. 3. *Global cognitive functioning.* Forest plot illustrating effect sizes and 95 % credible intervals for each study assessing global cognitive functioning. Positive values indicate that the cognitive intervention is more effective than the activities performed by the control group.

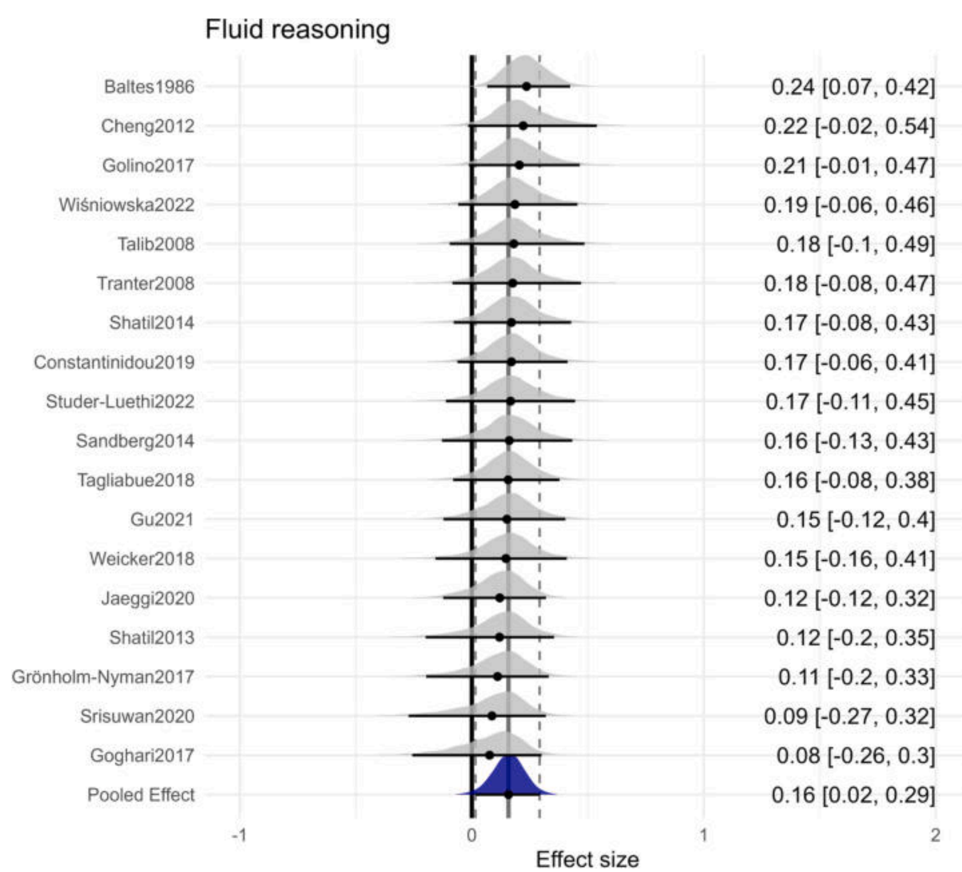

Fig. 4. *Fluid reasoning.* Forest plot illustrating effect sizes and 95 % credible intervals for each study assessing fluid reasoning. Positive values indicate that the cognitive intervention is more effective than the activities performed by the control group.

overall weighted effect size was 0.14 (95 % CI [0.06, 0.23]), meaning that in general short-term memory cognitive interventions are more effective than activities performed by the control groups, despite the small effect size. Heterogeneity across studies was tau = 0.06 (95 % CI

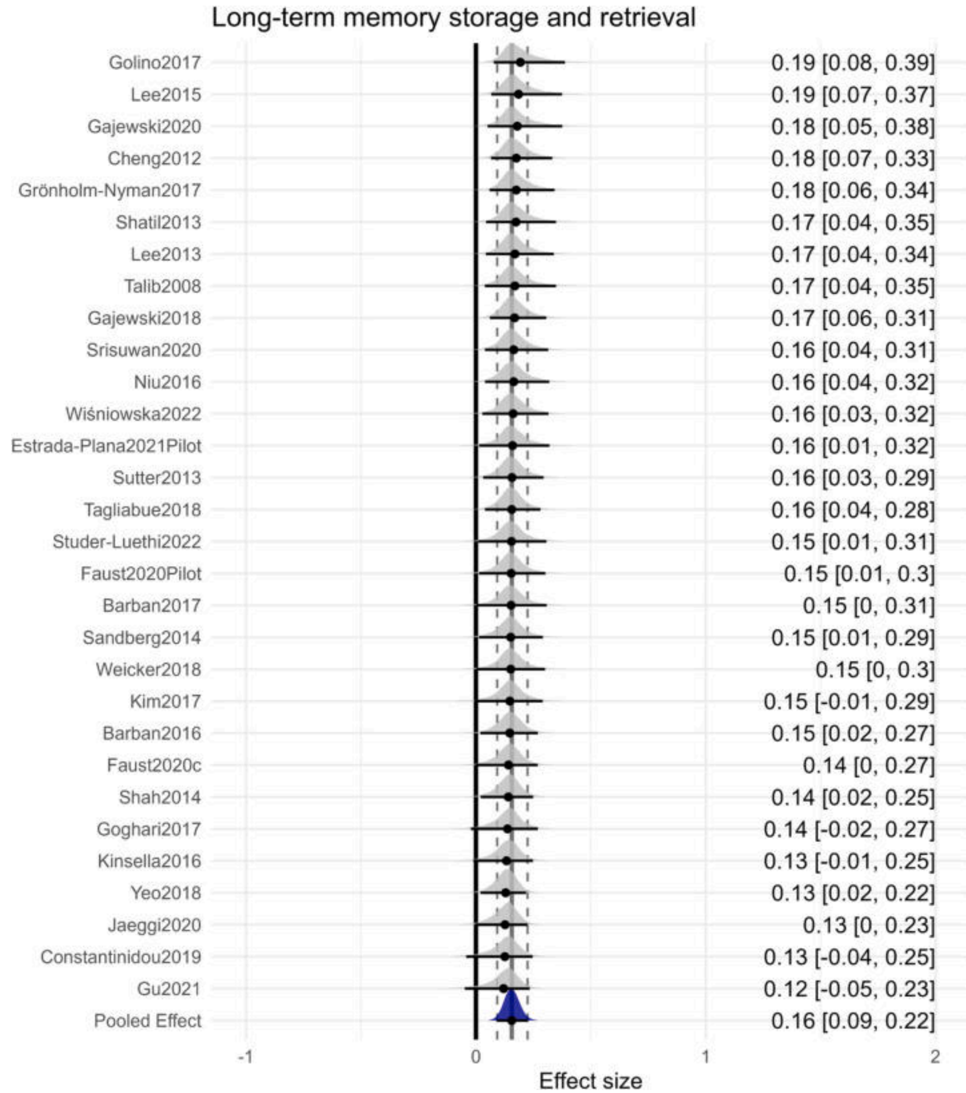

Fig. 5. *Long-term memory storage and retrieval.* Forest plot illustrating effect sizes and 95 % credible intervals for each study assessing long-term memory storage and retrieval. Positive values indicate that the cognitive intervention is more effective than the activities performed by the control group.

[0.00, 0.17]); heterogeneity across outcomes was tau = 0.09 (95 % CI [0.00, 0.20]). Fig. 6 shows the forest plot with outcomes aggregated within studies. Results from the linear regression test of the funnel plot indicated that the data included are symmetric (bias = −0.19; se = 0.56; t (60) = -0.33, p = 0.74), suggesting the absence of publication bias. Posterior Predictive Check results are reported in the Supplementary Materials. In the analysis that took into account only works without a severe or critical level of risk of bias, the overall weighted effect size was 0.10 (95 % CI [0.01, 0.20]). Heterogeneity across studies was tau = 0.06 (95 % [0.00, 0.17]); heterogeneity across outcomes was tau = 0.07 (95 % [0.00, 0.19]). The complete results (outliers, points of influence, forest plot, posterior predictive check) are reported in the Supplementary Materials.

3.4.4. *Executive functions*

A total of 688 experimental subjects and 657 control participants from 96 outcomes and 24 studies were included in the meta-analysis about the efficacy of cognitive interventions on executive functions. The analysis revealed the presence of fourteen extreme outcomes (Binder et al., 2016; Constantinidou, 2019; Gu et al., 2021; Jaeggi et al., 2020; Niu et al., 2016; Pothier et al., 2021; Sandberg et al., 2014; Sutter et al., 2013; Wiśniowska et al., 2024), of which two are from Grönholm-Nyman et al., (2017) and three are from Van Muijden et al., (2012). Due to being outliers, they were removed from the original set of data. Two influential points were detected from the same study (Jaeggi et al., 2020). The overall weighted effect size was 0.17 (95 % CI [0.10, 0.25]), which is considered small. It indicated that cognitive interventions were more effective than activities performed by the control groups in this cognitive domain. Heterogeneity across studies was tau = 0.07 (95 % CI [0.00, 0.18]); heterogeneity across outcomes was tau = 0.07 (95 % CI [0.00, 0.17]). Fig. 7 shows the forest plot with outcomes aggregated within studies. Results from the linear regression test of the funnel plot indicated that the data included are symmetric (bias = 0.10; se = 0.40; t (94) = 0.25, p = 0.80), suggesting the absence of publication bias. Posterior Predictive Check results are reported in the Supplementary Materials. In the analysis that took into account only studies without a severe or critical level of risk of bias, the overall weighted effect size was 0.16 (95 % CI [0.07, 0.24]). Heterogeneity across studies was tau = 0.07 (95 % [0.0, 0.19]); heterogeneity across outcomes was tau = 0.07 (95 % [0.0, 0.17]). The complete results (outliers, points of influence, forest plot, posterior predictive check) are reported in the Supplementary Materials.

3.4.5. *Processing speed*

A total of 947 experimental subjects and 903 control participants from 45 outcomes and 29 studies were included in the meta-analysis

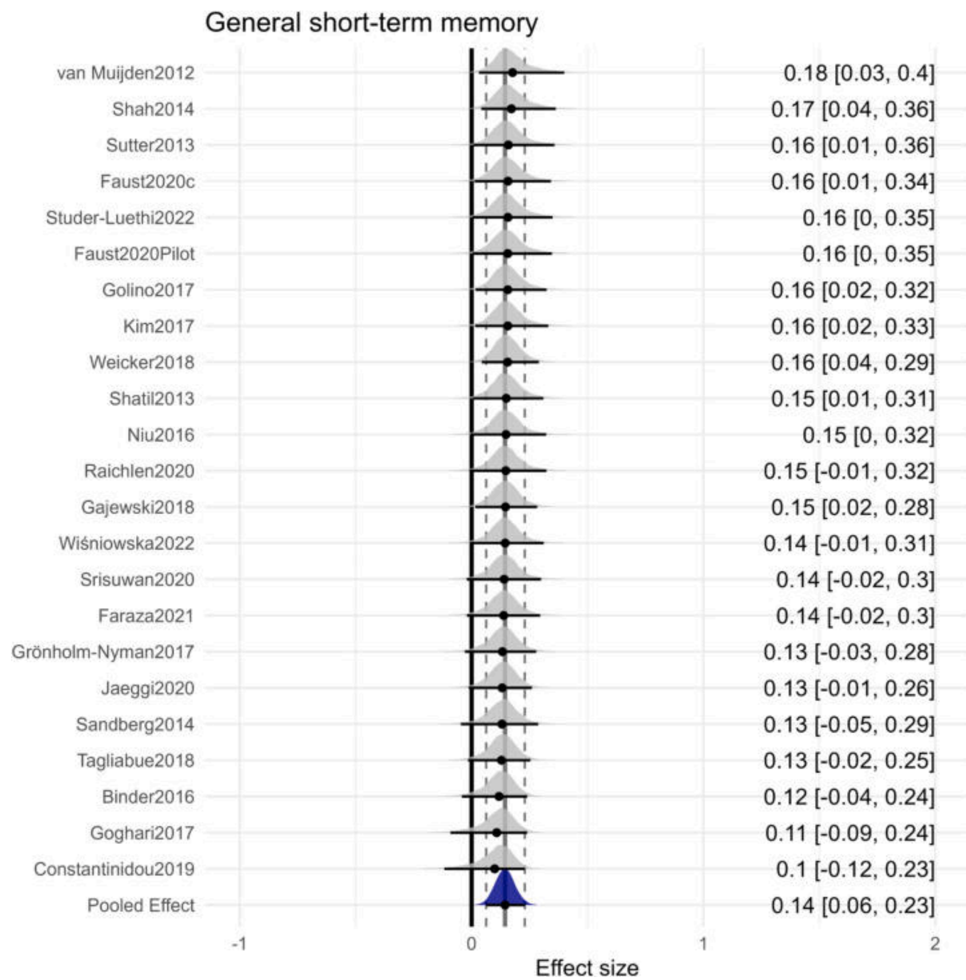

Fig. 6. *General short-term memory.* Forest plot illustrating effect sizes and 95 % credible intervals for each study assessing general short-term memory. Positive values indicate that the cognitive intervention is more effective than the activities performed by the control group.

about the efficacy of cognitive interventions on processing speed. Two outcomes from Van Muijden et al., (2012) study were excluded from the original set of processing speed data, as outliers. The study by Yeo and colleagues (2018) represented an influential point. The overall weighted effect size was 0.10 (95 % CI [0.01, 0.20]), suggesting the effectiveness of the cognitive interventions against the control group activities in processing speed, despite the small effect size. Heterogeneity across studies was tau = 0.09 (95 % CI [0.00, 0.22]); heterogeneity across outcomes was tau = 0.06 (95 % CI [0.00, 0.16]). Fig. 8 shows the forest plot with outcomes aggregated within studies. Results from the linear regression test of the funnel plot indicated that the data included are asymmetric (bias = 0.93; se = 0.39; t (43) = 2.39, p = 0.02), suggesting the possible presence of publication bias. Posterior Predictive Check results are reported in the Supplementary Materials. In the analysis that considered only works without a severe or critical level of risk of bias, the overall weighted effect size was 0.08 (95 % CI [-0.03, 0.19]). Heterogeneity across studies was tau = 0.08 (95 % [0.00, 0.21]); heterogeneity across outcomes was tau = 0.06 (95 % [0.00, 0.17]). The complete results (outliers, points of influence, forest plot, posterior predictive check) are reported in the Supplementary Materials.

3.4.6. *Visual processing*

A total of 432 experimental subjects and 453 control participants from 13 outcomes and 12 studies were included in the meta-analysis about the efficacy of cognitive intervention on visual processing. The analysis revealed the presence of an influential point (Yeo et al., 2018) and no outliers. The overall weighted effect size was 0.22 (95 % CI [0.04, 0.40]), which is considered small; it revealed that the cognitive interventions are more effective on visual processing than the activities performed by the control group. Heterogeneity across studies was tau = 0.12 (95 % CI [0.01, 0.34]); heterogeneity across outcomes was tau = 0.11 (95 % CI [0.00, 0.31]). Fig. 9 shows the forest plot with outcomes aggregated within studies. Results from the linear regression test of the funnel plot indicated that the data included are symmetric (bias = −0.42; se = 0.85; t (11) = -0.49, p = 0.63), suggesting the absence of publication bias. Posterior Predictive Check results are reported in the Supplementary Materials.

In this specific domain, no outcomes had a severe or critical level of risk of bias, indeed no further analyses were performed.

3.5. *Psychiatric and psychological outcomes*

Due to the extremely reduced number of outcomes for self-awareness (Shatil, 2013), psychiatric symptoms (Estrada-Plana et al., 2021; Millán-Calenti et al., 2015; Shah et al., 2014; Sutter et al., 2013), and functional capacity (Srisuwan et al., 2020), meta-analysis could not be performed on these domains.

3.5.1. *Quality of life*

A total of 117 experimental subjects and 107 control participants from 9 outcomes and 3 studies (i.e., Estrada-Plana et al., 2021; Shah et al., 2014; Shatil et al., 2014) were included in the meta-analysis about the efficacy of cognitive intervention on quality of life. The analysis revealed the presence of six influential points, of which three are from

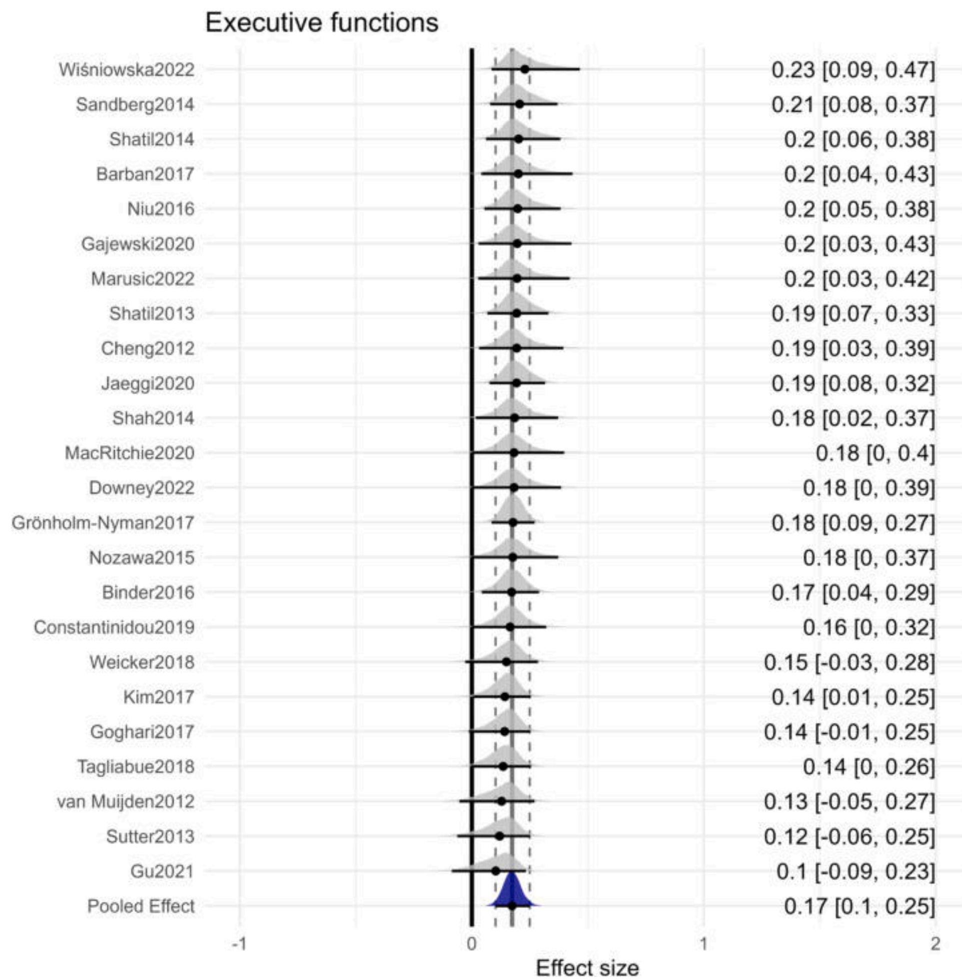

Fig. 7. *Executive functions.* Forest plot illustrating effect sizes and 95 % credible intervals for each study assessing executive functions. Positive values indicate that the cognitive intervention is more effective than the activities performed by the control group.

Estrada-Plana et al., (2021), two are from Shah et al. (2014) and one is from Shatil et al. (2014). No outliers were detected. The overall weighted effect size was 0.14 (95 % CI [-0.48, 0.83]), revealing no differences between the cognitive interventions and the activities performed by the control group. Heterogeneity across studies was tau = 0.33 (95 % CI [0.01, 1.20]); heterogeneity across outcomes was tau = 0.28 (95 % CI [0.01, 0.86]). Fig. 10 shows the forest plot with outcomes aggregated within studies. Results from the linear regression test of the funnel plot indicated that the data included are almost symmetric (bias = 1.58; se = 0.73; $t(7) = 2.15$, $p = 0.07$), suggesting the absence of publication bias. Posterior Predictive Check results are reported in the Supplementary Materials.

In the current domain, 8 out of the 9 outcomes had a severe level of risk of bias. Therefore, in this case, no further analysis could be conducted.

3.5.2. *Reported cognitive complaints*

A total of 165 experimental subjects and 151 control participants from 11 outcomes and 5 studies were included in the meta-analysis about the efficacy of cognitive intervention on reported cognitive complaints. The analysis revealed the presence of an influential point and one outlier, both by Kinsella et al. (2015) study. The outlier was removed from the original set of records. The overall weighted effect size was −0.06 (95 % CI [-0.38, 0.26]), revealing no differences between the cognitive interventions and the activities performed by the control group. Heterogeneity across studies was tau = 0.15 (95 % CI [0.01, 0.52]); heterogeneity across outcomes was tau = 0.30 (95 % CI [0.05, 0.59]). Fig. 11 shows the forest plot with outcomes aggregated within studies. Results from the linear regression test of the funnel plot indicated that the data included are symmetric (bias = −0.79; se = 1.85; $t(9) = -0.43$, $p = 0.68$), suggesting the absence of publication bias. Posterior Predictive Check results are reported in the Supplementary Materials. In the analysis that considered only studies without a severe or critical level of risk of bias, the overall weighted effect size was −0.16 (95 % CI [-0.69, 0.37]), with also a significant worsening in heterogeneity both across studies and across outcomes, respectively tau = 0.25 (95 % [0.01, 0.90]) and tau = 0.44 (95 % [0.20, 0.83]); the complete results (outliers, points of influence, forest plot, posterior predictive check) are reported in the Supplementary Materials.

3.6. *Neurophysiological outcome*

Due to the reduced number of studies including neurophysiological outcomes (Lampit et al., 2015; Niu et al., 2016; Talib et al., 2008) and their heterogeneity (i.e., RS-fRMI, ERP, fMRI, DTI, metabolites and platelet PLA_2) meta-analysis could not be performed on these domains.

3.7. *Qualitative assessment*

We considered as confounding domains participants' age and gender, the cognitive performance before the intervention, any measure of cognitive reserve (e.g., education), and possible self-enrollment in the study.

Among the 51 included studies, the overall risk of bias was rated as

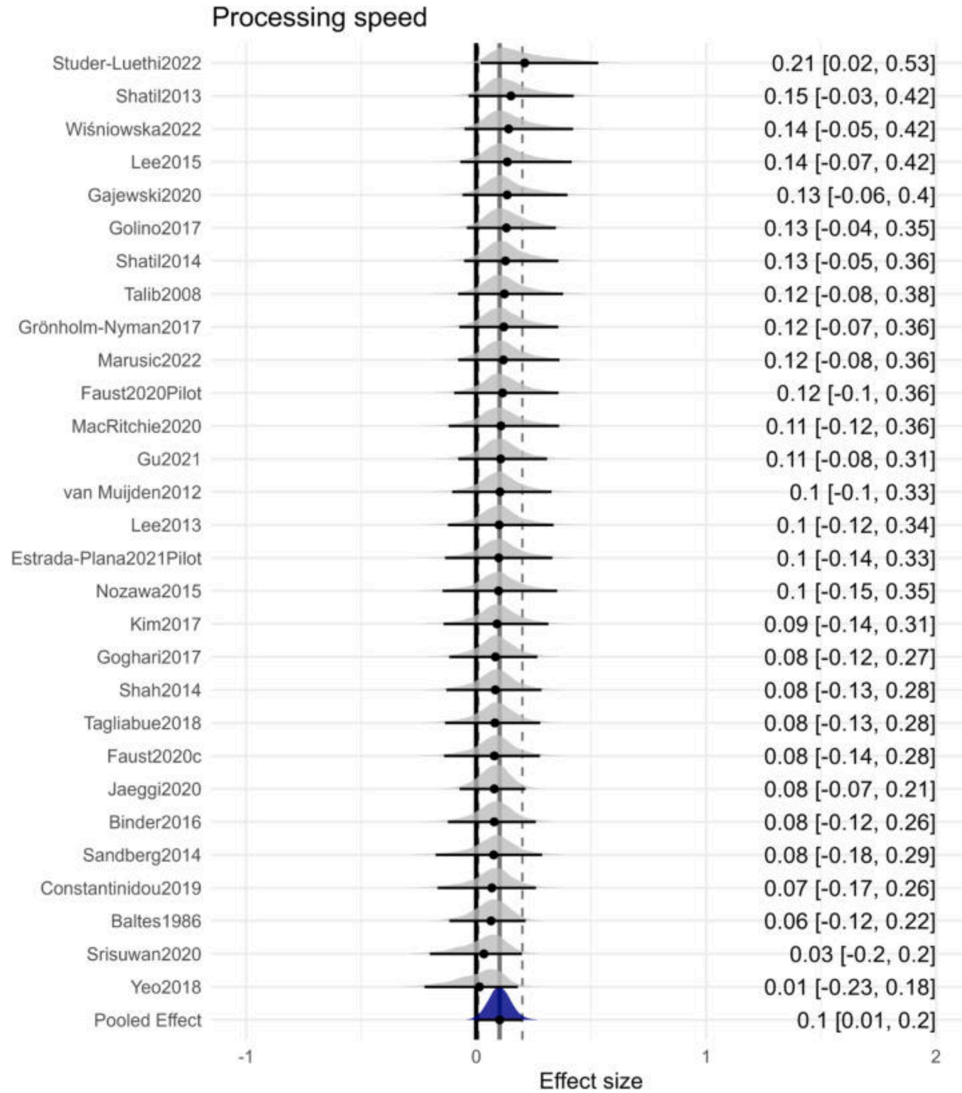

Fig. 8. *Processing speed.* Forest plot illustrating effect sizes and 95 % credible intervals for each study assessing processing speed. Positive values indicate that the cognitive intervention is more effective than the activities performed by the control group.

moderate in the majority of the studies (n = 29; 56.86 %), serious in 21 studies (41.18 %), and critical in one study (1.96 %). No study was judged to have a low overall risk of bias.

Considering each domain, the qualitative assessment indicated a low risk for bias due to participant selection (96.08 %), intervention classification (96.08 %), intervention deviation (68.63 %), missing data (72.55 %), measurement outcomes (50.98 %), and selection of the reported result (86.27 %). Moderate risk of bias was most frequently observed in the domains of confounding (68.63 %) and outcomes measurement (41.17 %). Serious risk of bias was less common, primarily identified in the domains of confounding (17.65 %) and deviations from intended interventions (13.73 %). A critical risk of bias was identified in only one study, specifically related to participant selection (see Table 2 in Supplementary Materials).

4. Discussion

Our study aimed to conduct a comprehensive and updated systematic review of existing literature on cognitive interventions, quantifying their impact on cognitive functioning and psychological components in healthy older adults. To this aim, we applied a Bayesian multi-level meta-analytic approach. Our work included 51 articles in the systematic review and 43 in the meta-analysis.

Overall, our review highlighted that cognitive interventions predominantly consisted of multidomain cognitive training, delivered through technological methods, often in group settings and via face-to-face modality. It was also observed that the "at distance" modality of administration was not widely adopted. A mere 20 % of the included studies utilised the intervention, despite its apparent enhanced feasibility. The underlying reasons for this phenomenon may not be attributable to the impact of the pandemic, as only three of the ten articles in question have been published in the period subsequent to 2020. Instead, it may be explained by the fact that older adults are the least digitally literate group in the population, facing more barriers, displaying more negative attitudes towards technology and less willingness to adopt technologies than younger individuals (Zhang, 2023). Therefore, adopting this mode of administration may present additional challenges for researchers, particularly in terms of participant recruitment and the allocation of resources to support participants in becoming familiar with the technological tool.

Control groups in the included studies were typically active and no-treatment groups. Limited attention was given to long-term follow-ups (single and multiple) and psychological outcomes (e.g., psychiatric measures, quality of life). Interventions ranged from a minimum of 5 to a maximum of 50 sessions, mostly held three times a week, for approximately one hour per session. In some cases, essential aspects of the

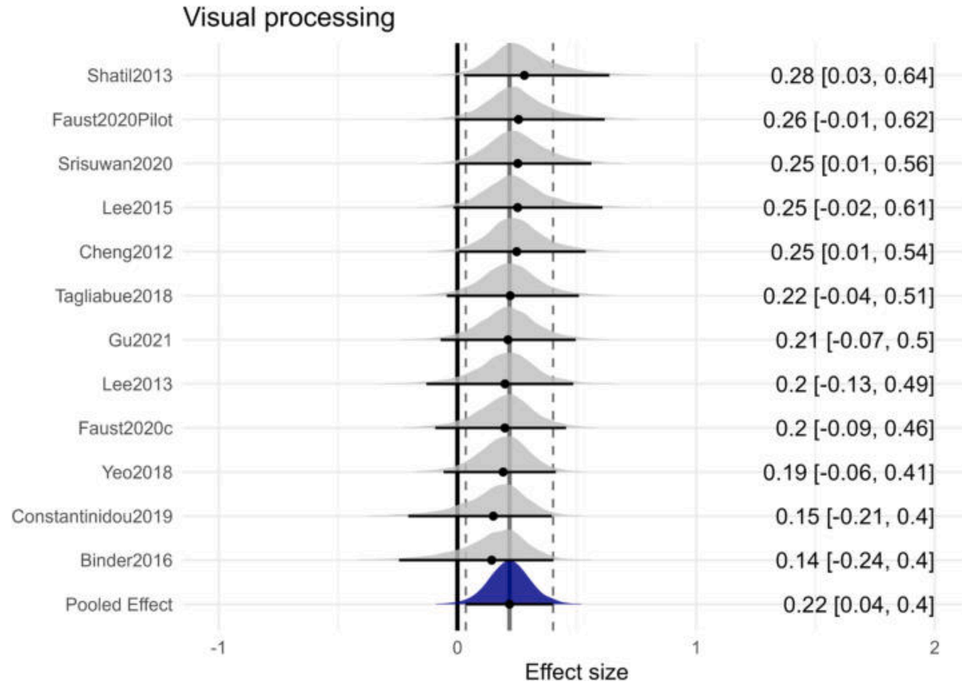

Fig. 9. *Visual processing.* Forest plot illustrating effect sizes and 95 % credible intervals for each study assessing visual processing. Positive values indicate that the cognitive intervention is more effective than the activities performed by the control group.

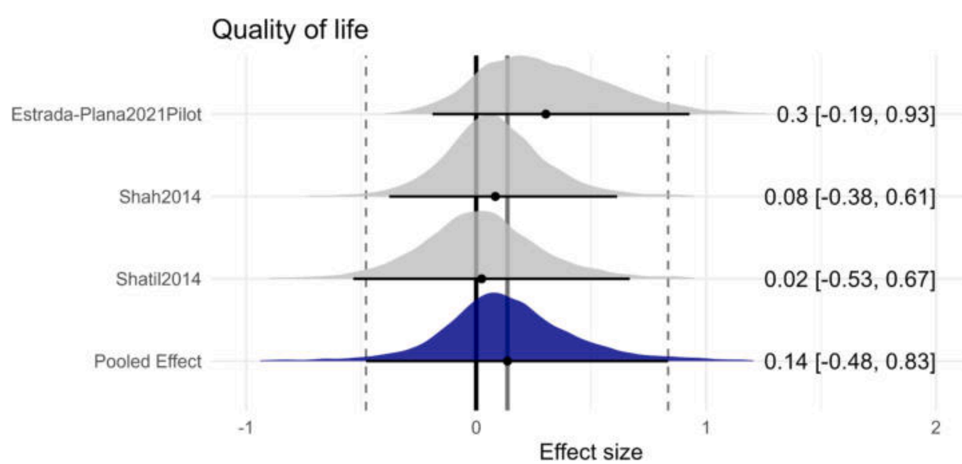

Fig. 10. *Quality of life.* Forest plot illustrating effect sizes and 95 % credible intervals for each study assessing quality of life. Positive values indicate that the cognitive intervention is more effective than the activities performed by the control group.

interventions - such as the format, the method and the modality of administration - were not clearly reported; from an Open Science perspective, failing to report these qualitative characteristics adequately represents a significant limitation, as it interferes with the precise replication of the design, the intervention, and, consequently, the findings in future research.

Regarding the meta-analysis, it primarily focused on global cognitive functioning assessed through screening tests, like the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS; Randolph et al., 1998), used in 54 % of cases. Cognitive interventions, compared to control activities, demonstrated moderate effectiveness in promoting improvements in overall cognition, with smaller effects observed in other cognitive domains examined, including fluid reasoning, long-term memory storage and retrieval, general short-term memory, executive functions, processing speed, and visual processing.

In contrast, uncertain effects were found on quality of life or individuals' reported cognitive complaints. Regarding self-awareness, neurophysiological outcome and psychiatric symptoms, as previously indicated, it was not possible to determine whether cognitive interventions had an impact on them for the lack of data. We identified only one study assessing the functional capacity domain (i.e., independence), which is in line with the inclusion criteria targeting healthy older adults, for whom significant functional decline is not typically expected and, indeed, measured.

Overall, the results appeared robust, as shown by the lack of evidence of publication bias, with the exceptions of processing speed, long-term memory storage, and retrieval. The multi-level analysis approach further enhanced the robustness of our results by accounting for the structure of the data. In fact, it allowed us to minimize the risk of false-positive results and to obtain more realistic estimates of heterogeneity, which we found to be relatively small. In particular, processing speed, executive functions, and memory (i.e., long- and short-term) revealed very low heterogeneity. We found slightly higher values for global functioning, fluid reasoning, visual processing, quality of life and

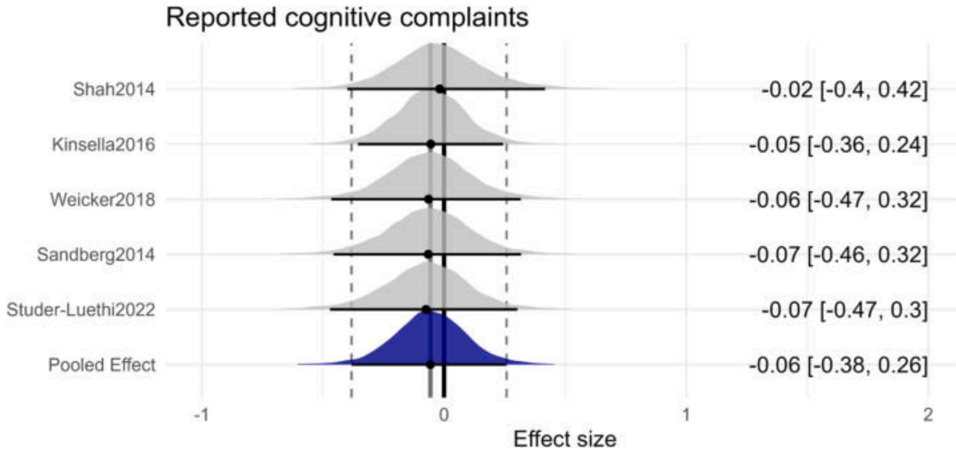

Fig. 11. *Reported cognitive complaints.* Forest plot illustrating effect sizes and 95 % credible intervals for each study assessing reported cognitive complaints. Positive values indicate that the cognitive intervention is more effective than the activities performed by the control group.

reported cognitive complaints. Crucially, higher heterogeneity characterised outcomes for which a lower number of studies was available. This result serves to corroborate the necessity for further evidence in order to achieve findings that are both solid and credible.

The robustness of our findings also appears to be supported by additional analyses conducted after excluding those studies with severe or critical risk of bias, thus retaining only those with moderate risk. Across most of the examined domains, no meaningful differences were found in either effect size or heterogeneity, with results remaining substantially unchanged compared to the previous analyses. The only exceptions were the fluid reasoning and processing speed domains. In both cases, we found a low probability that the effect would be zero, likely because the studies with the strongest estimated effect were characterized by a severe risk of bias. Moreover, in the domain of reported cognitive complaints, we observed a detrimental change in both effect size and heterogeneity. In this case, the effect even appeared to favor the control group rather than the experimental group, contrary to what would be expected. However, it is important to note that the effect size in this domain was already negative in the previous analysis, and the confidence interval crossed zero, suggesting an unreliable effect. Moreover, the number of included studies decreased from five to three. Overall, this finding confirms that the results obtained in this domain (and more in general, in all the psychological domains examined) remain untrustworthy.

The observed efficacy of cognitive interventions - particularly regarding our primary outcome - can be understood in light of the cumulative contribution of single cognitive domains to overall functioning. In this sense, the improvements in global cognitive performance may likely reflect the combined effects of gains across the specific domains that compose it. This interpretation is supported by the nature of the screening tests used to assess global cognition, which inherently integrate multiple domains, including memory, executive functions, processing speed, fluid reasoning, short-term memory, and visual processing. Importantly, it should also be noted that when executive functions are specifically trained, as is the case in most of the included unidomain cognitive interventions, targeting them may contribute to broader cognitive improvements in older adults, given their central role in global cognitive processing (Nguyen et al., 2019).

Overall, the findings related to cognitive functioning can be considered encouraging, particularly given the many individual variables that influence the effectiveness of these interventions. Firstly, it is important to highlight that cognitive functioning level and the extent to which it declines vary considerably between older individuals. Furthermore, a single training program may not be equally effective for everyone, due to various individual factors, such as cognitive reserve (Mondini et al., 2016) and personality traits (Marr et al., 2020). These factors might somewhat explain why we did not find an effect in a component like quality of life, a domain where we potentially had sufficient data to conduct a meta-analysis. Perhaps personalized interventions tailored to participants' individual characteristics should lead not only to cognitive improvements, but also to greater psychological engagement and everyday life impact, by better aligning with each person's unique traits.

In general, our results were in line with findings from Kelly et al. (2014), the most comparable work to ours, which also showed positive effects of cognitive training on executive functions and global cognition, compared to active control groups, and on memory, compared to no intervention. While they reported improvements in subjective cognitive performance (i.e., reported cognitive complaints), our work did not replicate this result, likely due to scarcity of data. Furthermore, in our study, the effectiveness of cognitive interventions, compared to control groups, was evaluated without distinguishing between cognitive training (CT) and cognitive stimulation (CS), since only three articles could be classified as cognitive stimulation interventions, considering Clare and Woods' (2004) definition. This limitation mirrored those noted by Kelly et al., who also reported difficulties in pooling data due to intervention heterogeneity. In this specific context, despite the conceptual systematization carried out by Clare and Woods (2004), the distinction between cognitive training and cognitive stimulation remains somewhat ambiguous in the scientific literature. This also results in a classification that is not always realistic and representative of the type of treatment actually used. In the current work, while we emphasized the different types of cognitive interventions, we decided not to exclude the three articles involving cognitive stimulation from the meta-analyses, since the preregistered aim of this work was to include both interventions. Like cognitive training, cognitive stimulation represents a form of cognitive intervention and, despite their peculiarities, both share the same purpose, namely, to promote the improvement and maintenance of cognitive functioning as people age.

Importantly, our study differed in several respects from that of Kelly and colleagues (2014). First, we assessed a broader range of cognitive domains, allowing for a more comprehensive evaluation of the effects of cognitive interventions. In addition to cognitive outcomes, we also aimed to examine the impact of these interventions on psychological variables (e.g., psychiatric symptoms). However, as previously noted, incomplete data and the inconsistent administration of psychological questionnaires, often limited to either the pre- or post-intervention phase, prevented us from fully addressing this aspect. This limitation underscores the importance of systematically incorporating psychological variables in future intervention research.

Also, in contrast to Kelly and colleagues (2014), we did not carry out separate meta-analysis by control group type (e.g., cognitive intervention vs no-treatment control group; cognitive intervention vs active control group), because we did not find any substantial heterogeneity between outcomes or studies. The absence of heterogeneity suggested that there was no evidence of any factor modifying or impacting the effects, including the control group type. In general, our approach to control groups differed: when a study included multiple control groups, we selected the most active one (e.g., physical activity groups) wherever possible. Choosing active, more stringent control groups over inactive or no-treatment controls led to a more conservative approach when comparing the experimental and control groups. Comparing a group that underwent a cognitive intervention with one that did not receive any treatment would have only allowed us to discuss that cognitive training or stimulations are more effective than doing nothing. However, the aim of the current work was to establish whether engaging in specific cognitive interventions yields more benefits than carrying out more general and broad activities (such as those typically performed by active control groups). While this approach might reduce the likelihood of obtaining a non-zero effect size, any positive effect size would yield stronger conclusions for our research question.

Some limitations of our study should be pointed out. First, it must be acknowledged that publication bias was observed in two of the examined cognitive domains (i.e., long-term memory storage and retrieval and processing speed). This suggests a potentially incomplete and less objective representation of the effectiveness of cognitive interventions in these domains. Also, the risk of bias assessment revealed an overall moderate to serious methodological quality risk among the included studies. However, it is important to note that in most studies, the majority of individual domains were rated as having a low risk of bias, with only a few, specifically bias due to confounding, outcome measurement, and deviations from intended intervention, showing higher levels of risk. In this context, it is worth noting that the quality assessment of the included studies reveals that the scientific literature on cognitive interventions, specifically in healthy older adults, is limited and not always of high methodological quality (absence of follow-up assessments, small sample size, intervention characteristics not always clearly reported, etc.). This, in turn, makes it more difficult to conduct a meta-analysis that can reliably evaluate the effectiveness of these interventions. To address this problem, we included, for each outcome, a supplementary meta-analysis that excluded the studies characterized by a severe risk of bias. These supplementary analyses largely confirm the main results, suggesting that our primary results are reliable. This work serves a dual purpose: first, it rigorously exposes the methodological limitations and moderate risk of bias within the existing literature. Second, it integrates this evidence to provide the most comprehensive quantitative summary currently available. While these results accurately reflect the published evidence, their value is contingent upon the quality of the inputs. We stress that our pooled estimates must be considered carefully, as they mirror the limitations inherent in the literature we synthesized.

Besides that, we never found high heterogeneity either across studies. On one hand, this suggests a general consistency in training effects, but on the other, it is also important to note that the intervention protocols themselves were highly heterogeneous (e.g., method of administration, format, timing, frequency). This lack of heterogeneity in outcomes, despite the variability in interventions, may reflect a lack of specificity regarding what elements of the training could be more effective than others, thereby complicating the formulation of a more targeted intervention. The taxonomy used for categorizing outcomes into broad ability domains could be a limitation, too. Adopting a taxonomy to group and synthesize outcomes from a large variety of tests inevitably means that the classification may not always be precise and may overlook cognitive subcomponents that could be clinically relevant. Nonetheless, for statistical purposes, it should be noted that adopting a more stringent and detailed classification of outcomes would have significantly reduced the number of outcomes available within each cognitive domain.

It should also be highlighted that our study focuses on changes in neuropsychological test scores immediately following the completion of the cognitive intervention. As a result, no information is available regarding the long-term duration of any treatment effects. Among the articles included in our review, 14 contained a single follow-up, while only 2 included multiple follow-ups. The limited number of articles, combined with the subsequent grouping of their outcomes into broad ability domains, did not provide sufficient data to draw conclusions about the maintenance of cognitive intervention effects over time.

5. Conclusions

Overall, we found that cognitive interventions were moderately effective in improving global cognitive functioning and all the other broad cognitive domains (i.e., fluid reasoning, long-term memory storage and retrieval, general short-term memory, executive functions, processing speed, and visual processing), although with smaller effects.

This review highlighted the lack of post-intervention follow-up assessments, as well as the limited inclusion of psychological outcome measures. The latter factor strongly indicates that more evidence is necessary to investigate the possible effectiveness of cognitive interventions on psychological components. Given their importance not only as outcomes following a cognitive intervention but also as individual characteristics of participants, future studies on these treatments should consider incorporating measures that assess psychological components at baseline, post-intervention and follow-up.

Our findings support the moderate effectiveness of this type of cognitive intervention in the context of healthy aging, despite the numerous individual variables that may influence outcomes. These results highlight the need for continued research in this area, with particular emphasis on the development of increasingly personalized approaches. Taking into account not only the structural characteristics of cognitive interventions (e.g., format, mode of delivery) but also individual differences among participants may lead to more effective, well-received, and widely adopted interventions.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neubiorev.2026.106571.

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