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Review article

Components of effective exergame-based training to improve cognitive functioning in middle-aged to older adults – A systematic review and meta-analysis

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ABSTRACT

Background: Exergame-based training is currently considered a more promising training approach than conventional physical and/or cognitive training.
Objectives: This study aimed to provide quantitative evidence on dose-response relationships of specific exercise and training variables (training components) of exergame-based training on cognitive functioning in middle-aged to older adults (MOA).
Methods: We conducted a systematic review with meta-analysis including randomized controlled trials comparing the effects of exergame-based training to inactive control interventions on cognitive performance in MOA.
Results: The systematic literature search identified 22,928 records of which 31 studies were included. The effectiveness of exergame-based training was significantly moderated by the following training components: body position for global cognitive functioning, the type of motor-cognitive training, training location, and training administration for complex attention, and exercise intensity for executive functions.
Conclusion: The effectiveness of exergame-based training was moderated by several training components that have in common that they enhance the ecological validity of the training (e.g., stepping movements in a standing position). Therefore, it seems paramount that future research focuses on developing innovative novel exergame-based training concepts that incorporate these (and other) training components to enhance their ecological validity and transferability to clinical practice. We provide specific evidence-based recommendations for the application of our research findings in research and practical settings and identified and discussed several areas of interest for future research.
PROSPERO registration number: CRD42023418593; prospectively registered, date of registration: 1 May 2023

Abbreviations: $CI_{95\,\%}$, 95 % confidence intervals; Df, degrees of freedom; K, number of studies; MIDE, Multidisciplinary Iterative Design of Exergames; MOA, middle-aged to older adults; N, total analyzed sample size; P, p-value; PERSiST, implementing Prisma in Exercise, Rehabilitation, Sport medicine and SporTs science; PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analyses; PROSPERO, international prospective register of systematic reviews; Q_M, Cochrane's Q of the model; RCTs, randomized controlled trials; SDs, standard deviations; TESTEX, Tool for the Assessment of Study Quality and Reporting in Exercise.

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1. Introduction

1.1. Background

The projected increase in neurocognitive disorders poses a significant challenge to aging societies (World Health Organization, 2021). For instance, the global number of individuals with neurocognitive disorders such as preclinical, prodromal, and manifest Alzheimer's Disease were estimated at 315, 69, and 32 million, respectively - representing 22 % of all persons aged 50 years and above (Gustavsson et al., 2023). To mitigate this emerging public health problem, it is essential to develop and implement sustainable and effective interventions for the prevention of neurocognitive disorders (World Health Organization, 2021). Physical exercise was recently recommended for the primary, secondary, and tertiary prevention of neurocognitive disorders by a panel of international experts in a collaborative guideline (Veronese et al., 2023). According to the 'guided plasticity facilitation' framework (Fabel and Kempermann, 2008; Herold et al., 2018; Kempermann et al., 2010), the combination of physical and cognitive exercises enhances neuroplasticity due to the positive synergistic effects of the "facilitating effects" of physical exercise and the "guiding effects" of cognitive exercises. The "facilitating effect" refers to specific neurophysiological mechanisms that are triggered by physical exercise and which promote neuroplasticity (e.g., the higher release of brain-derived neurotrophic factor), while the "guiding effect" encompasses the cognitive stimulation processes which are assumed to "guide" such neuroplastic changes. (Fabel and Kempermann, 2008; Herold et al., 2018; Kempermann et al., 2010) Although some evidence did not support these positive synergistic effects (Embrechts et al., 2023; Hu et al., 2022), most systematic reviews and meta-analyses provide evidence for the (limited) superiority of combined and/or simultaneous motor-cognitive training over isolated physical or cognitive training for improving cognitive functioning in MOA (Biazus-Sehn et al., 2020; Gallou-Guyot, Mandigout, Combourieu-Donnezan, et al., 2020; Gómez-Soria et al., 2022; Meng et al., 2022; Rieker et al., 2022; Torre and Temprado, 2022b; Yang et al., 2020; Zhao et al., 2022). As a result, simultaneous motor-cognitive training is currently considered the most effective type of training for improving cognitive functioning in middle-aged to older adults (MOA) with and without cognitive impairment (Blomstrand et al., 2023; Gavelin et al., 2021).

In recent years, exergaming has become increasingly popular as a promising option for engaging MOA in simultaneous motor-cognitive training (Valenzuela et al., 2018). Exergaming involves technology-driven physical activities, such as playing video games, that require participants to be physically active or exercise in order to play the game (Witherspoon, 2013). Exergame-based training has several advantages over conventional motor-cognitive training because it provides structured and scalable training options with multisensory feedback and the opportunity for repetitive practice in an enriched and standardized environment, which can enhance skill acquisition and neuroplasticity (Aminov et al., 2018). Based on their ease of use in clinical or home-based settings and relatively low costs to implement and deliver motor-cognitive training, exergames may also optimize the utilization of healthcare resources (Chen et al., 2023; Prosperini et al., 2021; Stanmore et al., 2019). Moreover, exergame-based training has a high level of acceptance and enjoyment among MOA (Gallou-Guyot, Mandigout, Bherer, et al., 2020; Gallou-Guyot et al., 2022; Mura et al., 2018; Nawaz et al., 2016; Valenzuela et al., 2018), which facilitates training motivation (Mura et al., 2018; Valenzuela et al., 2018; Zhao et al., 2020) and promotes positive behavioral changes (Ryan and Deci, 2000) through the internalization of motivation (Manser, Poikonen, et al., 2023; Zhao et al., 2020), resulting in high adherence to the training (Chu et al., 2022; Gallou-Guyot, Mandigout, Bherer, et al., 2020; Gallou-Guyot et al., 2022; Mura et al., 2018; Swinnen et al., 2022; Valenzuela et al., 2018; Zhao et al., 2020) and potentially further facilitating the trainings' effectiveness (Chen et al., 2023; Panza et al., 2018).

As a result, exergame-based training is currently considered a more promising training approach than conventional physical and cognitive training (Stojan and Voelcker-Rehage, 2019; Temprado, 2021; Torre and Temprado, 2022b). Systematic reviews and meta-analyses have shown that exergame-based training was effective in improving cognitive performance in MOA (Gallou-Guyot, Mandigout, Bherer, et al., 2020; Jiang et al., 2022; Torre and Temprado, 2022a) as well as MOA with a range of clinical conditions, including mild (Cai et al., 2023; Zhao et al., 2020) to major (Cai et al., 2023; Swinnen et al., 2022; Zhao et al., 2020) neurocognitive disorder, mixed populations of individuals with neurological disabilities (Li et al., 2022), older adults living in long-term care facilities (Chen et al., 2023), or individuals who suffered a stroke (Aminov et al., 2018). However, the evidence for the effects on cognitive performance in individuals with Parkinson's disease remains inconclusive (Gallou-Guyot et al., 2022). Additionally, when specifically comparing exergame-based training to conventional physical and cognitive training, the current state of evidence is inconclusive given that recent systematic reviews and meta-analyses have found significant effects in favor of exergaming (Cai et al., 2023; Jiang et al., 2022; Stojan and Voelcker-Rehage, 2019), while others have not (Chen et al., 2023; Chen et al., 2023; Soares et al., 2021; Torre and Temprado, 2022a) or have found even smaller effects compared to simultaneous motor-cognitive training (Gavelin et al., 2021). The inconsistent findings are likely due to the considerable heterogeneity of training outcomes across studies, which can be attributed to the large variation in the design of exergame-based training approaches, including but not limited to the frequent use of commercially available products (Temprado, 2021). Commercially available products often lack adequate theoretical underpinnings regarding their design, neglect basic training and neuroplasticity principles, and are not specifically designed for the needs of a specific target population, or the context in which they are applied and investigated (Gallou-Guyot, Mandigout, Bherer, et al., 2020; Temprado, 2021; Valenzuela et al., 2018). To overcome these limitations, the assumption that well-designed and tailored exergame-based interventions can lead to more pronounced effects on cognitive functioning seems justified (Stojan and Voelcker-Rehage, 2019).

Torre and Temprado (2022) (Torre and Temprado, 2022a) proposed two complementary approaches to overcome the current limitations in the field: One suggestion was to design, develop, and tailor new exergame-based training concepts to the specific needs of the populations of MOA using an "intervention first" rather than a "product first" approach (Torre and Temprado, 2022a). In this respect, the Medical Research Council's guidelines for the development and evaluation of complex interventions (Skivington et al., 2021) as well as the Multidisciplinary Iterative Design of Exergames (MIDE) – Framework (Li et al., 2020) provide guidance on how to optimally structure this process (see (Manser and de Bruin, 2021) for an application example). However, this process also strongly relies on the integration of evidence from empirical studies. In this context, the second suggestion of Torre and Temprado (2022) (Torre and Temprado, 2022a) was that the scientific community should establish a consensus on a protocol that should be followed in future studies (Torre and Temprado, 2022a).

To facilitate this process, Torre and Temprado (2022) (Torre and Temprado, 2022a) conducted the most comprehensive analysis to date of specific exercise and training variables (training components) that contribute to the effectiveness of exergame-based training to influence cognitive functioning in the aging population. Although Torre and Temprado's suggestions of specific standards for the design and evaluation of exergame-based training studies are a major step to push the field forward (Torre and Temprado, 2022a), their analysis of the state of the literature has three important limitations. First, their analysis was based on a qualitative synthesis of the evidence (i.e., no meta-analysis with moderator or subgroup analyses). Second, the lack of information on specific training components that were insufficiently reported in the original publications limiting their subsequent qualitative analysis of the

literature. Third, other potentially important components of exergame-based training, such as body position during training, training density, level of cognitive demands, training location, specificity of the training, or whether it was delivered in a group or individually, were not considered in their analysis. (Torre and Temprado, 2022a) Cognizant of the aforementioned limitations, future efforts are necessary to extend the findings of previous work (Torre and Temprado, 2022a) and identify in a more robust manner the training components that can influence the effectiveness of exergame-based training to preserve or improve cognitive performance in MOA.

1.2. Objectives with PICO-scheme

This study aimed to provide quantitative evidence of which training components influence the effectiveness of exergame-based training (**I**ntervention) on cognitive functioning (**O**utcome) in MOA (mean age $\geq$ 50 years) (**P**articipants) compared to inactive control interventions (i.e. sham control, usual care or lifestyle, or no intervention; **C**omparison).

In this context, we aimed to analyze the influence of the following training components: (i) the type of motor-cognitive training (i.e. as defined by (Herold et al., 2018) as 'simultaneous-incorporated' ("Moving while Thinking") and 'simultaneous-additional' ("Thinking while Moving") motor-cognitive training (Herold et al., 2018)), (ii) all basic exercise and training variables (i.e. exercise intensity, exercise duration, type of exercise (in the context of this review: types of motor cognitive training (see above), training frequency, training density, and training duration), as defined in (Herold et al., 2019)), (iii) training volume (per week and in total), (iv) training location, (v) training administration (i.e., performed individually, performed in a group, or mixed approaches), (vi) supervision of training, (e) individualization of training (i.e., generic (one size fits all) versus tailored), (vii) specificity of training (i.e., the exergame-based intervention was designed with a focus on (a) cardiorespiratory training, (b) training of neurocognitive functioning, (c) strength training, or (d) multicomponent training), (viii) body position during training (i.e., 'standing - stepping incl. weight shifting' versus 'standing - mainly weight shifting' versus 'sitting'), (ix) design of the exergames (i.e., recreational games versus serious games (games developed with a purpose beyond play) as defined in (Michael and Chen, 2005; Rego et al., 2010)), and (x) level of cognitive demand of the exergames.

2. Methods

This systematic review and meta-analysis was conducted and reported in accordance with the established guidelines from the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) 2020 guideline (Page, McKenzie, et al., 2021) together with its explanation and elaboration paper (Page, Moher, et al., 2021) (checklist see supplementary file 1) and the PERSiST (implementing PRISMA in Exercise, Rehabilitation, Sport medicine and SporTs science) guidance (Ardern et al., 2022).

2.1. Protocol and registration

A protocol for this systematic review and meta-analysis was developed in accordance with the Cochrane Handbook for Systematic Review of Interventions (Cumpston et al., 2019) as well as established guidelines from the PRISMA-Protocols 2015 Statement (Moher et al., 2015). This systematic review and meta-analysis was registered at the international prospective register of systematic reviews (PROSPERO) before starting this systematic review (ID = CRD42023418593; date of registration: 1 May 2023). There were no relevant amendments to the study protocol after its registration.

2.2. Eligibility criteria

Randomized controlled trials (RCTs) assessing the effectiveness of exergame-based training compared to inactive control interventions in MOA were considered eligible. More specifically, we used the following eligibility criteria (see Table 1):

2.3. Information sources

In the ordered library search, the digital databases Medline, Embase, CINAHL, APA PsycINFO, Cochrane Library, Web of Science Core Collection, Scopus, and Pedro were consulted for publications up to 9 May 2023 by a professional librarian of the University of Zurich.

2.4. Search strategy

We developed a search strategy based on the PICOS approach (i.e., acronym for **P**opulation, **I**ntervention, **C**omparison, **O**utcomes, and **S**tudy type) and predefined eligibility criteria in collaboration with a professional librarian. The librarian then translated the strategy into precise search strings for each database. The search strings consisted of Medical Subject Headings, free text words, and Boolean operators. The search strings were constructed to combine predefined terms for

Table 1
Description of all eligibility criteria.

Inclusion criteria:	Exclusion criteria:
1. Participants:middle-aged to older human adults (mean age $\geq$ 50 years; including healthy middle-aged to older adults as well as middle-aged to older adults with any type of clinical condition(s)).	1. Study type: review articles, meta-analyses, pilot or feasibility studies as defined in (Eldridge et al., 2016), preliminary reports, dissertations, conference abstracts, posters, and study protocols.
2. Interventions:exergame- (as defined by (Witherspoon, 2013)) based training (as defined in (Herold et al., 2019)).	2. Accessibility: full text was not accessible via institutional subscription or interlibrary loan, or was not provided by the authors within a 30-day response window.
3. Comparison:inactive control interventions (i.e. sham control, usual care or lifestyle, or no intervention).	3. Language: articles not written in English
4. Outcomes:cognitive functioning (i.e., evaluated via standardized and clinically validated neuropsychological tests that assess, but are not limited to, global cognitive functioning as well as the key neurocognitive domains (as defined in (Sachdev et al., 2014) in line with the fifth version of the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2013)) of (1) learning and memory, (2) complex attention, (3) executive function, and (4) visuospatial skills).	
5. Study Type:randomized controlled trials, regardless of whether they were conducted in a parallel, crossover, or factorial design.	
Publication:published in a reputable[a] peer-reviewed scientific journal	

Abbreviations: Diagnostic and Statistical Manual of Mental Disorders 5th Edition

[a] The judgement of whether a journal was reputable was made by agreement between the two reviewers, taking into account a number of criteria, including indexing of the journal in one of the online databases considered for this review, transparent reporting of peer review policies, and no evidence of predatory journals (e.g, lack of transparency about their publication process, fees, and policies, low or no standards for acceptance or articles, no or private instead of institutional email addresses provided for editors-in-chief, suspiciously low or high article processing fees, suspiciously fast publication times, unprofessional website design (e.g., frequent spelling and grammatical errors)).

population, intervention, outcome, and study type. Within these groups, all terms were combined with OR operators. The search strings were applied without any filtering options or limits. Please refer to Supplementary File 2 for the complete search strategy, including all search strings and results of the ordered library search.

2.5. Study selection and data collection

2.5.1. Data management and selection process

All records were systematically screened using EPPI-Reviewer software (Version: 6.15.0.0) (Thomas et al., 2023). The provided standard coding scheme was adapted to meet all eligibility criteria. The screening- and selection process was pilot-tested and executed by two independent reviewers (PM, FH) according to a predefined screening protocol (Supplementary File 3). The retrieved results were matched and discussed for final inclusion (PM, FH). In case of disagreements, EdB served as referee. By calculating Cohen's kappa, the strength of the inter-rater agreement of the study selection process was rated as poor (0), slight (0.1 – 0.20), fair (0.21 – 0.40), moderate (0.41 – 0.60), substantial (0.61 – 0.80), or almost perfect (0.81 – 1.0) (Cohen, 1960; Landis and Koch, 1977; McHugh, 2012).

2.5.2. Data collection process

EPPI-Reviewer software (Version: 6.15.0.0) (Thomas et al., 2023) was used to extract relevant data in accordance with to the Cochrane Handbook for Systematic Review of Interventions (Cumpston et al., 2019) by PM. FH cross-checked the extracted data after completion of the data collection process. In case of mismatches, EdB inspected the discrepancies and decided on the final data set. To ensure a thorough analysis, we made up to three separate attempts to contact the corresponding and/or last author of the study to supplement our dataset for analysis in cases where the publications lacked sufficient or clear information. We included all data that was received by our communicated deadline of December 13, 2023.

2.6. Data items

Data was extracted from each included study on: (1) study characteristics (i.e. author, year of publication, study design), (2) population characteristics, including type of population (i.e., healthy MOA vs. MOA with clinical condition(s)), cognitive status (i.e., healthy vs. cognitively impaired) and demographic information (i.e., age, sex, body mass index, duration of education), (3) all exergaming components defined in section '1.2 Objectives', (4) information on completion adherence (i.e., percentage of participants completing the study in each group) and attendance adherence (i.e., defined as *"the proportion between the number of sessions attended and the number of sessions offered, reported in percentage"* (Di Lorito et al., 2020)) of the training, as well as occurrence of adverse events, (5) type of outcome measure for all standardized and clinically-validated neuropsychological tests that assess, but are not limited to, global cognitive performance as well as the key neurocognitive domains (as defined in (Sachdev et al., 2014) in line with the fifth version of the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2013)) of (a) learning and memory, (b) complex attention, (c) executive function, and (d) visuospatial skills, and (6) findings of each study relating to cognitive performance. We classified the extracted data into the predefined categories to ensure that our extracted data met the definitions for each data item defined here.

2.7. Risk of bias in individual studies

Risk of bias of the included studies was assessed by two independent raters (PM, FH) using a modified version (Herold et al., 2023) of the Tool for the Assessment of Study Quality and Reporting in Exercise (TESTEX) scale (Smart et al., 2015). If publications lacked sufficient or clear information, we made up to three separate attempts to contact the corresponding and/or last author of the study to obtain the necessary information for rating the risk of bias. We chose not to calculate a summary score due to the drawbacks of this method (Büttner et al., 2020). Any discrepancies were resolved by a discussion among the two raters. In case of disagreements, EdB served as referee. Inter-rater agreement was again assessed and interpreted based on Cohen's kappa (Cohen, 1960; Landis and Koch, 1977; McHugh, 2012).

2.8. Data synthesis

Data was synthesized in accordance with the Cochrane Handbook for Systematic Review of Interventions (Cumpston et al., 2019; Higgins et al., 2019). In cases in which only nonparametric data were reported, we estimated means and standard deviations (SDs) based on Wan's formulas (Wan et al., 2014). In cases in which the SDs of the change scores were not reported, these were calculated from the reported data using the statistical methods described in the Cochrane Handbook for Systematic Review of Interventions (Cumpston et al., 2019; Higgins et al., 2019). Particularly, we first calculated the correlations between the pre- and post-measurements and then used these correlation coefficients to calculate the SDs for the change scores for each group. If the reported data did not allow for these imputations, particularly because the correlation coefficient was typically not reported and could not be calculated from the available data, we made up to three separate attempts to contact the corresponding and/or last author of the study to obtain this information and/or the raw data from the studies. (Cumpston et al., 2019; Higgins et al., 2019) If unsuccessful, we calculated the SDs of the change scores by assigning a correlation coefficient of $r = 0.7$. This allowed us to obtain a conservative estimate of the treatment effect (Rosenthal, 1991), as has been done in previous meta-analyses (Berlim et al., 2017; Kallapiran et al., 2015; McGirr et al., 2015; Papadopoulos et al., 2020; Yagiz et al., 2022). If all these steps were unsuccessful, the corresponding studies were excluded from the meta-analysis.

A pooled estimate of the treatment effect was then calculated for each neurocognitive domain. We used the change scores from post-measurement to baseline for the exergame-based training intervention (s) and control condition(s). When studies measured multiple outcomes that we classified within the same neurocognitive domain, we calculated the standardized mean difference and standard error for each outcome. We then created a composite score for each neurocognitive domain by taking the mean of these values.

A meta-analysis was performed in accordance with the recommendations of the Cochrane Handbook for Systematic Review of Interventions (Cumpston et al., 2019; Deeks et al., 2019). A random-effects model from the 'metafor' package (Viechtbauer, 2010) with the Hedges estimator (Hedges, 1983, 1992) was used to calculate standardized mean differences (Hedge's g) and 95 % confidence intervals ($CI_{95\,\%}$). The data were presented in the form of forest plots. The significance level was set at $p \leq 0.05$ (two-sided), and effect sizes were interpreted as small (Hedge's $g < 0.5$), medium ($0.5 \geq$ Hedge's $g < 0.8$), or large (Hedge's $g \geq 0.8$) (Cohen, 1988).

To analyze which exergame-based training components influence the effectiveness on cognitive performance in MOA compared to inactive control interventions, planned moderator analyses were conducted for all pre-specified training components (see section '2.6 Data Items') with pre-specified subgroups. Results were presented in tabular form. We also used pre-specified subgroups for continuous variables (i.e., exercise duration, training frequency, training duration, training volume, and attendance adherence), because it was unreasonable to assume a linear relationship between these continuous variables and effect sizes.

A planned subgroup analysis was performed for the type of population and cognitive status. Finally, planned sensitivity analyses were performed for the quality of the included studies and for adherence to training. In line with established recommendations, the planned moderator analyses, subgroup analyses and sensitivity analyses were only performed for the neurocognitive domains with at least 10 studies

(Cumpston et al., 2019; Deeks et al., 2019).

2.9. Risk of bias and heterogeneity across studies

Between-study heterogeneity was assessed using Cochrane Q in accordance with the I^2 statistic (Higgins and Thompson, 2002). Funnel plots (i.e., standard errors) were assessed both visually and formally using Egger's test (Egger et al., 1997; Sterne and Egger, 2001) to detect possible publication bias. When publication bias was indicated, sensitivity analyses were conducted using the trim and fill method for random-effects models. The trim and fill method redresses asymmetries in funnel plots by adjusting the point estimate of the pooled effect size and $CI_{95\,\%}$ for missing studies (Duval and Tweedie, 2000).

3. Results

3.1. Study selection

The systematic search for publications identified 22,928 records. After removal of duplicates (number of studies (k) = 10,545), automatic screening by study type classifiers, and screening on title and abstract (k = 9472), 71 articles were included for full-text screening, 31 studies (Adcock et al., 2020; Benitez-Lugo et al., 2022; Chan et al., 2019; de Bruin Eling et al., 2020; Delbroek et al., 2017; Gschwind Yves et al., 2015; Gunst et al., 2022; Henrique Patricia Paula et al., 2023; Hoang et al., 2016; Hou et al., 2023; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Kim et al., 2021; Liu et al., 2022; Maillot et al., 2012; Moret et al., 2022; Ordnung et al., 2017; Perrot et al., 2021; Phirom et al., 2020; Robert et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022; Zheng et al., 2022) were included for the qualitative synthesis, and - if data were extractable - were considered for the meta-analyses (k = 31) (Adcock et al., 2020; Benitez-Lugo et al., 2022; Chan et al., 2019; de Bruin Eling et al., 2020; Delbroek et al., 2017; Gschwind Yves et al., 2015; Gunst et al., 2022; Henrique Patricia Paula et al., 2023; Hoang et al., 2016; Hou et al., 2023; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Kim et al., 2021; Liu et al., 2022; Maillot et al., 2012; Moret et al., 2022; Ordnung et al., 2017; Perrot et al., 2021; Phirom et al., 2020; Robert et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022; Zheng et al., 2022). See Fig. 1 for a detailed overview of the study selection.

3.2. Study characteristics

The included studies were conducted between 2012 (Maillot et al., 2012) and 2023 (Henrique Patricia Paula et al., 2023; Hou et al., 2023) and were designed as parallel group (Adcock et al., 2020; Benitez-Lugo et al., 2022; Chan et al., 2019; de Bruin Eling et al., 2020; Delbroek et al., 2017; Gschwind Yves et al., 2015; Henrique Patricia Paula et al., 2023; Hoang et al., 2016; Hou et al., 2023; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Kim et al., 2021; Liu et al., 2022; Maillot et al., 2012; Moret et al., 2022; Ordnung et al., 2017; Perrot et al., 2021; Phirom et al., 2020; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Swinnen et al., 2021; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022; Zheng et al., 2022) or cluster (Gunst et al., 2022; Robert et al., 2021; Stanmore et al., 2019) RCTs.

3.3. Participant characteristics

The studies included healthy MOA (k = 16) (Adcock et al., 2020; Benitez-Lugo et al., 2022; Chan et al., 2019; Gschwind Yves et al., 2015; Henrique Patricia Paula et al., 2023; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Kim et al., 2021; Maillot et al., 2012; Moret et al., 2022; Ordnung et al., 2017; Phirom et al., 2020; Schoene et al., 2013; Schoene et al., 2015; Zhao et al., 2022; Zhao et al., 2022), a mixed population of healthy MOA and MOA with amnestic mild neurocognitive disorder (k = 1) (Jirayucharoensak et al., 2019), or MOA with the following clinical condition(s): coronary artery disease (k = 1) (Vieira et al., 2018), Down syndrome (k = 1) (Perrot et al., 2021), (care-dependent) MOA that are residents of a nursing home or assisted living facilities with a variety of clinical conditions (not further specified; k = 4) (de Bruin Eling et al., 2020; Gunst et al., 2022; Jahouh et al., 2021; Stanmore et al., 2019), hypertension (k = 1) (Hou et al., 2023), (institutionalized) MOA with mild (k = 3) (Delbroek et al., 2017; Liu et al., 2022; Robert et al., 2021) to major (k = 4) (Robert et al., 2021; Swinnen et al., 2021; Zheng et al., 2022) neurocognitive disorder, multiple sclerosis (k = 1) (Hoang et al., 2016), and Parkinson's Disease (k = 1) (Song et al., 2018). Thirty-two percent of studies included cognitively impaired participants (Delbroek et al., 2017; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Liu et al., 2022; Perrot et al., 2021; Robert et al., 2021; Stanmore et al., 2019; Swinnen et al., 2021; Vieira et al., 2018; Zheng et al., 2022). Overall, the studies included 1611 participants (76.9 % female) with a mean age of 72.4 ± 12.7 years.

3.4. Characteristics of the interventions

Below we provide a summary of the key characteristics of the interventions. For a more detailed overview, refer to supplementary file 4.

3.4.1. Details on basic exercise variables

Exergaming was implemented as simultaneous-incorporated (k = 29; 94 % of studies) (Adcock et al., 2020; Benitez-Lugo et al., 2022; Chan et al., 2019; de Bruin Eling et al., 2020; Delbroek et al., 2017; Gunst et al., 2022; Henrique Patricia Paula et al., 2023; Hoang et al., 2016; Hou et al., 2023; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Liu et al., 2022; Maillot et al., 2012; Moret et al., 2022; Ordnung et al., 2017; Perrot et al., 2021; Phirom et al., 2020; Robert et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022; Zheng et al., 2022) or simultaneous-additional (k = 2; 6 % of studies) (Gschwind Yves et al., 2015; Kim et al., 2021) motor-cognitive training at a light (k = 6; 19 % of studies) (Delbroek et al., 2017; Gunst et al., 2022; Hoang et al., 2016; Perrot et al., 2021; Stanmore et al., 2019; Swinnen et al., 2021), moderate (k = 6; 19 % of studies) (Adcock et al., 2020; Hou et al., 2023; Liu et al., 2022; Maillot et al., 2012; Vieira et al., 2018; Zhao et al., 2022), vigorous (k = 1; 3 % of studies) (Zhao et al., 2022), or not reported (k = 18; 58 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; de Bruin Eling et al., 2020; Gschwind Yves et al., 2015; Henrique Patricia Paula et al., 2023; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Kim et al., 2021; Moret et al., 2022; Ordnung et al., 2017; Phirom et al., 2020; Robert et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Zheng et al., 2022) exercise intensity and an exercise duration of ≤ 15 min (k = 6; 19 % of studies) (de Bruin Eling et al., 2020; Robert et al., 2021; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Zheng et al., 2022), > 15 to ≤ 30 min (k = 9; 29 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; Delbroek et al., 2017; Hoang et al., 2016; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Kim et al., 2021; Schoene et al., 2013; Schoene et al., 2015), > 30 to ≤ 45 min (k = 3; 10 % of studies) (Adcock et al., 2020; Jahouh et al., 2021; Moret et al., 2022), or > 45 min (k = 12; 39 % of studies) (Gschwind Yves et al., 2015; Gunst et al., 2022; Henrique Patricia Paula et al., 2023; Hou et al., 2023; Liu et al., 2022; Maillot et al., 2012; Ordnung et al., 2017; Perrot et al., 2021; Phirom et al., 2020; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022) per session or was not reported (k = 1, 3 % of studies) (Jirayucharoensak et al., 2019).

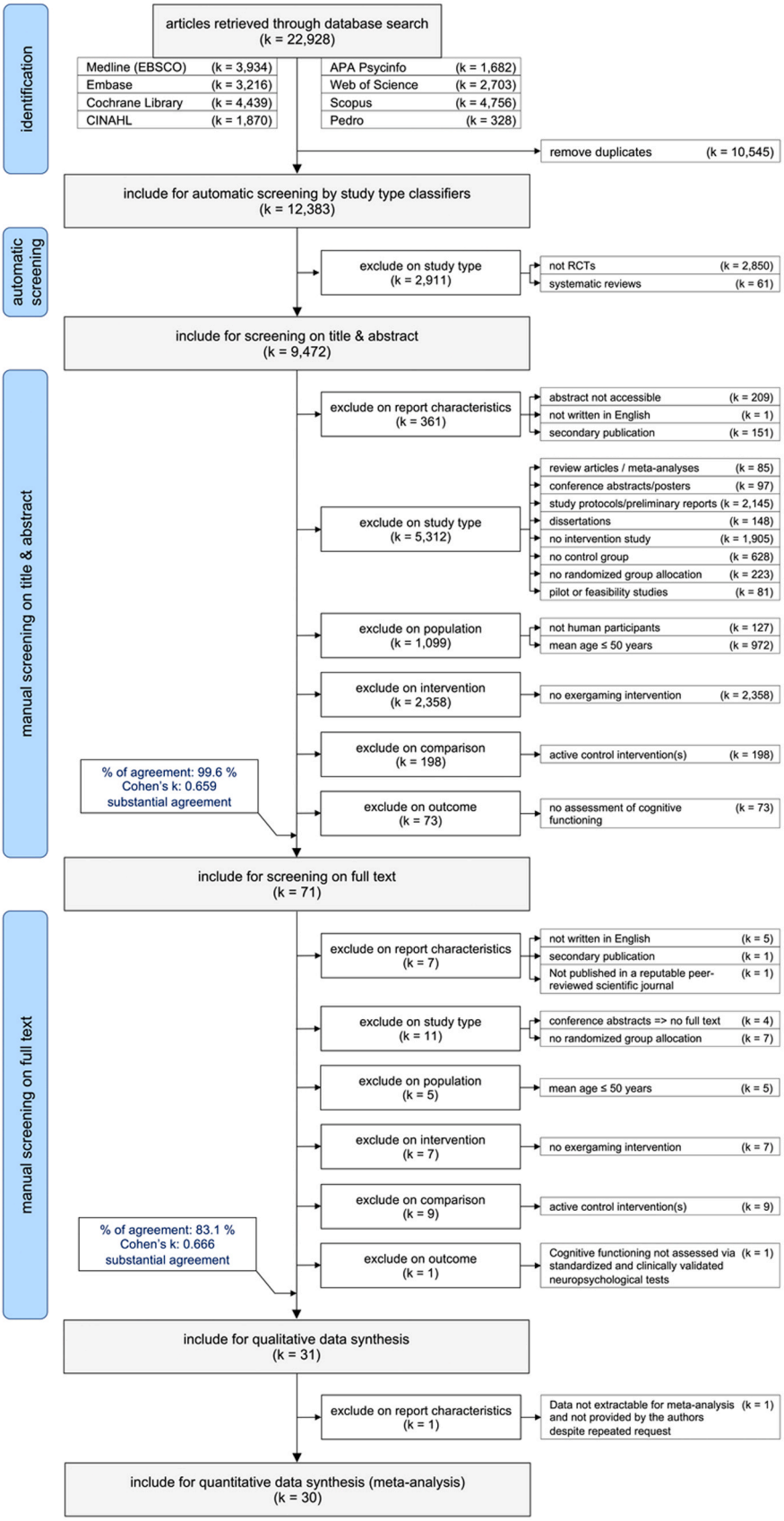


Fig. 1. flow diagram of the search-, screening- and study selection process.

3.4.2. Details on basic training variables

The training frequency was ≤ 2x/week (k = 10; 32 % of studies) (Benitez-Lugo et al., 2022; Delbroek et al., 2017; Gunst et al., 2022; Henrique Patricia Paula et al., 2023; Hoang et al., 2016; Kim et al., 2021; Maillot et al., 2012; Ordnung et al., 2017; Perrot et al., 2021; Robert et al., 2021), 3x/week (k = 20; 65 % of studies) (Adcock et al., 2020; Chan et al., 2019; de Bruin Eling et al., 2020; Gschwind Yves et al., 2015; Hou et al., 2023; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Liu et al., 2022; Moret et al., 2022; Phirom et al., 2020; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022), or ≥ 4x/week (k = 1; 3 % of studies) (Zheng et al., 2022) with a training duration of ≤ 4 weeks (k = 2; 6 % of studies) (de Bruin Eling et al., 2020; Moret et al., 2022), 5–8 weeks (k = 10; 32 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; Delbroek et al., 2017; Henrique Patricia Paula et al., 2023; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Ordnung et al., 2017; Schoene et al., 2013; Swinnen et al., 2021; Zheng et al., 2022), 9–12 weeks (k = 12; 39 % of studies) (Hoang et al., 2016; Hou and Li, 2022; Kim et al., 2021; Liu et al., 2022; Maillot et al., 2012; Perrot et al., 2021; Phirom et al., 2020; Robert et al., 2021; Song et al., 2018; Stanmore et al., 2019; Zhao et al., 2022; Zhao et al., 2022), ≥ 13 weeks (k = 6; 19 % of studies) (Adcock et al., 2020; Gschwind Yves et al., 2015; Gunst et al., 2022; Hou et al., 2023; Schoene et al., 2015; Vieira et al., 2018), or was not reported (k = 1; 3 % of studies) (Jirayucharoensak et al., 2019). The resulting training volume was < 60 min (k = 8; 26 % of studies) (de Bruin Eling et al., 2020; Delbroek et al., 2017; Robert et al., 2021; Schoene et al., 2013; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Zheng et al., 2022), 60–119 min (k = 9; 29 % of studies) (Adcock et al., 2020; Benitez-Lugo et al., 2022; Chan et al., 2019; Hoang et al., 2016; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Kim et al., 2021; Schoene et al., 2015), 120–179 min (k = 9; 29 % of studies) (Gschwind Yves et al., 2015; Gunst et al., 2022; Henrique Patricia Paula et al., 2023; Liu et al., 2022; Maillot et al., 2012; Moret et al., 2022; Ordnung et al., 2017; Perrot et al., 2021; Zhao et al., 2022), or ≥ 180 min (k = 4; 13 % of studies) (Hou et al., 2023; Phirom et al., 2020; Vieira et al., 2018; Zhao et al., 2022) per week, and < 1000 min (k = 18; 58 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; de Bruin Eling et al., 2020; Delbroek et al., 2017; Henrique Patricia Paula et al., 2023; Hoang et al., 2016; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Kim et al., 2021; Moret et al., 2022; Ordnung et al., 2017; Robert et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Zheng et al., 2022), 1000 - 1499 min (k = 3; 10 % of studies) (Hou and Li, 2022; Maillot et al., 2012; Perrot et al., 2021), 1500 - 1999 min (k = 4; 13 % of studies) (Adcock et al., 2020; Gunst et al., 2022; Liu et al., 2022; Zhao et al., 2022), or ≥ 2000 min (k = 5; 16 % of studies) (Gschwind Yves et al., 2015; Hou et al., 2023; Phirom et al., 2020; Vieira et al., 2018; Zhao et al., 2022) in total. Training density was only reported by three studies (Adcock et al., 2020; Htut Thwe Zar et al., 2018; Robert et al., 2021) and could be obtained upon request from the authors for an additional five studies (Gunst et al., 2022; Maillot et al., 2012; Perrot et al., 2021; Swinnen et al., 2021; Zheng et al., 2022). It was classified as a between-session recovery time of ≥ 24 h but < 48 h (k = 1; 3 % of studies) (Adcock et al., 2020) or ≥ 48 h (k = 6; 19 % of studies) (Gunst et al., 2022; Htut Thwe Zar et al., 2018; Maillot et al., 2012; Perrot et al., 2021; Robert et al., 2021; Swinnen et al., 2021).

3.4.3. Details on other training components

The training was performed on-site (i.e., at a study center, clinic, or similar; k = 15; 48 % of studies) (Benitez-Lugo et al., 2022; de Bruin Eling et al., 2020; Delbroek et al., 2017; Gunst et al., 2022; Hou and Li, 2022; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Moret et al., 2022; Perrot et al., 2021; Phirom et al., 2020; Robert et al., 2021; Stanmore et al., 2019; Swinnen et al., 2021; Zhao et al., 2022; Zheng et al., 2022), at participants' homes (k = 9; 29 % of studies) (Adcock et al., 2020; Gschwind Yves et al., 2015; Hoang et al., 2016; Htut Thwe Zar et al., 2018; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Vieira et al., 2018; Zhao et al., 2022), with mixed approaches (k = 1; 3 % of studies) (Maillot et al., 2012), or training location was not reported (k = 6; 19 % of studies) (Chan et al., 2019; Henrique Patricia Paula et al., 2023; Hou et al., 2023; Kim et al., 2021; Liu et al., 2022; Ordnung et al., 2017). The training was performed individually (k = 15; 48 % of studies) (Adcock et al., 2020; Delbroek et al., 2017; Gschwind Yves et al., 2015; Hoang et al., 2016; Htut Thwe Zar et al., 2018; Moret et al., 2022; Perrot et al., 2021; Phirom et al., 2020; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Vieira et al., 2018; Zhao et al., 2022), in a group (k = 6; 19 % of studies) (Gunst et al., 2022; Hou and Li, 2022; Liu et al., 2022; Maillot et al., 2012; Zhao et al., 2022; Zheng et al., 2022), with mixed approaches (k = 1; 3 % of studies) (Robert et al., 2021), or training administration was not reported (k = 9; 29 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; de Bruin Eling et al., 2020; Henrique Patricia Paula et al., 2023; Hou et al., 2023; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Kim et al., 2021; Ordnung et al., 2017), and was fully supervised (k = 17; 55 % of studies) (Benitez-Lugo et al., 2022; Delbroek et al., 2017; Gunst et al., 2022; Hou et al., 2023; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Liu et al., 2022; Maillot et al., 2012; Moret et al., 2022; Ordnung et al., 2017; Perrot et al., 2021; Robert et al., 2021; Stanmore et al., 2019; Swinnen et al., 2021; Zhao et al., 2022; Zheng et al., 2022), partially supervised (k = 2; 6 % of studies) (Gschwind Yves et al., 2015; Song et al., 2018), unsupervised (k = 6; 19 % of studies) (Adcock et al., 2020; Hoang et al., 2016; Schoene et al., 2013, 2015; Vieira et al., 2018; Zhao et al., 2022), or supervision of training was not reported (k = 6; 19 % of studies) (Chan et al., 2019; de Bruin Eling et al., 2020; Henrique Patricia Paula et al., 2023; Jirayucharoensak et al., 2019; Kim et al., 2021; Phirom et al., 2020). The exergame-based interventions were individually tailored (k = 18; 58 % of studies) (Adcock et al., 2020; Delbroek et al., 2017; Gschwind Yves et al., 2015; Hou et al., 2023; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Liu et al., 2022; Moret et al., 2022; Phirom et al., 2020; Robert et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022), generic (one size fits all) (k = 5; 16 % of studies) (Gunst et al., 2022; Hoang et al., 2016; Maillot et al., 2012; Perrot et al., 2021; Zheng et al., 2022), or individualization of training was not reported (k = 8; 26 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; de Bruin Eling et al., 2020; Henrique Patricia Paula et al., 2023; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Kim et al., 2021; Ordnung et al., 2017). The training focused on neurocognitive functioning (k = 18; 58 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; de Bruin Eling et al., 2020; Delbroek et al., 2017; Hoang et al., 2016; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Kim et al., 2021; Moret et al., 2022; Phirom et al., 2020; Robert et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Swinnen et al., 2021; Zheng et al., 2022), strength (k = 1; 3 % of studies) (Henrique Patricia Paula et al., 2023), or was a multicomponent training (k = 12; 39 % of studies) (Adcock et al., 2020; Gschwind Yves et al., 2015; Gunst et al., 2022; Hou and Li, 2022; Liu et al., 2022; Maillot et al., 2012; Ordnung et al., 2017; Perrot et al., 2021; Stanmore et al., 2019; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022) for which serious games (k = 17; 55 % of studies) (Adcock et al., 2020; Benitez-Lugo et al., 2022; Delbroek et al., 2017; Gschwind Yves et al., 2015; Henrique Patricia Paula et al., 2023; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Kim et al., 2021; Liu et al., 2022; Moret et al., 2022; Phirom et al., 2020; Robert et al., 2021; Schoene et al., 2015; Stanmore et al., 2019; Swinnen et al., 2021; Vieira et al., 2018) or recreational games (k = 13; 42 % of studies) (de Bruin Eling et al., 2020; Gunst et al., 2022; Hoang et al., 2016; Hou et al., 2023; Hou and Li, 2022; Maillot et al., 2012; Ordnung et al., 2017; Perrot et al., 2021; Schoene et al., 2013; Song et al., 2018; Zhao et al., 2022; Zhao et al.,

2022; Zheng et al., 2022) were used, while we were unable to categorize this with the reported and/or provided information for one study (Chan et al., 2019). The body position of training was standing with stepping movements (and including weight shifting; k = 21; 68 % of studies) (Adcock et al., 2020; de Bruin Eling et al., 2020; Gschwind Yves et al., 2015; Gunst et al., 2022; Hoang et al., 2016; Hou and Li, 2022; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Liu et al., 2022; Maillot et al., 2012; Moret et al., 2022; Perrot et al., 2021; Phirom et al., 2020; Robert et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Swinnen et al., 2021; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022), standing with mainly weight shifting (k = 6; 19 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; Delbroek et al., 2017; Henrique Patricia Paula et al., 2023; Jirayucharoensak et al., 2019; Stanmore et al., 2019), or sitting (k = 2; 6 % of studies) (Kim et al., 2021; Zheng et al., 2022). For those studies that reported this information, mean completion adherence was 88.6 % for the exergame-based training (k = 29, total analyzed sample size (N) = 773) and 89.0 % for the inactive control group (k = 29, N = 727), with a mean attendance adherence of 87.3 % (k = 19, N = 479) for the exergame-based training.

3.4.4. Details on interventions' safety

Regarding the safety of exergame-based training, one study reported a non-injurious fall during exergaming (Song et al., 2018), whereas the remaining studies did not report or declare any intervention-related (serious) adverse events (k = 18, 58 % of studies) (Adcock et al., 2020; de Bruin Eling et al., 2020; Delbroek et al., 2017; Gschwind Yves et al., 2015; Gunst et al., 2022; Hoang et al., 2016; Hou et al., 2023; Htut Thwe Zar et al., 2018; Liu et al., 2022; Maillot et al., 2012; Perrot et al., 2021; Phirom et al., 2020; Schoene et al., 2013; Schoene et al., 2015; Stanmore et al., 2019; Swinnen et al., 2021; Zhao et al., 2022; Zheng et al., 2022), or did not report information about its safety (k = 12, 39 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; Henrique Patricia Paula et al., 2023; Hou and Li, 2022; Jahouh et al., 2021; Jirayucharoensak et al., 2019; Kim et al., 2021; Moret et al., 2022; Ordnung et al., 2017; Robert et al., 2021; Vieira et al., 2018; Zhao et al., 2022).

3.4.5. Details on outcome measures

The neurocognitive domains measured included global cognition (k = 14, 45 % of studies) (Benitez-Lugo et al., 2022; Chan et al., 2019; Delbroek et al., 2017; Henrique Patricia Paula et al., 2023; Htut Thwe Zar et al., 2018; Jahouh et al., 2021; Kim et al., 2021; Liu et al., 2022; Phirom et al., 2020; Robert et al., 2021; Song et al., 2018; Stanmore et al., 2019; Swinnen et al., 2021; Zheng et al., 2022), complex attention (k = 17, 55 % of studies) (Adcock et al., 2020; Benitez-Lugo et al., 2022; de Bruin Eling et al., 2020; Gschwind Yves et al., 2015; Hoang et al., 2016; Hou and Li, 2022; Jirayucharoensak et al., 2019; Liu et al., 2022; Maillot et al., 2012; Moret et al., 2022; Ordnung et al., 2017; Perrot et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Vieira et al., 2018; Zhao et al., 2022), executive functions (k = 20, 65 % of studies) (Adcock et al., 2020; Benitez-Lugo et al., 2022; de Bruin Eling et al., 2020; Gschwind Yves et al., 2015; Gunst et al., 2022; Hoang et al., 2016; Hou et al., 2023; Hou and Li, 2022; Kim et al., 2021; Liu et al., 2022; Maillot et al., 2012; Moret et al., 2022; Ordnung et al., 2017; Perrot et al., 2021; Schoene et al., 2013; Schoene et al., 2015; Song et al., 2018; Vieira et al., 2018; Zhao et al., 2022; Zhao et al., 2022), learning & memory (k = 5, 16 % of studies) (Adcock et al., 2020; Hou and Li, 2022; Liu et al., 2022; Moret et al., 2022; Zhao et al., 2022), and visuospatial skills (k = 4, 13 % of studies) (Chan et al., 2019; Maillot et al., 2012; Schoene et al., 2015; Zhao et al., 2022).

3.5. Risk of bias within studies

The inter-rater agreement of the risk of bias rating was substantial (79.3 % of agreement; Cohen's k: 0.689) and all disagreement could be resolved between the two raters. The final rating (detailed in Fig. 2) revealed that the item with the lowest proportion of studies with a risk of bias was item 1 ('eligibility criteria specified') while there was an uncertain or high risk of bias for more than 50 % of studies in items 6 ('Completion adherence is ≥ 85 %'), 8 ('Adverse events have been reported'), 9 ('Intention-to-treat analysis was performed'), 12 ('Monitoring of the level of regular physical activity in the control group(s) has been conducted)', 13 ('Relative exercise intensity remained constant thought the physical training'), and 14 ('All exercise and training variables have been reported in sufficient detail').

3.6. Quantitative synthesis

A detailed overview of the retrieved data for each study and outcome can be found in supplementary file 5. All results of the meta-analyses for each neurocognitive domain, as well as the results of potential sources of between-study heterogeneity and publication bias, are shown in Fig. 3. In short, the pooled estimates showed significant effects in favor of exergame-based training for the neurocognitive domains of global cognition, complex attention, and executive functions, but no effects for learning and memory or for visuospatial skills. Effect estimates were small for all neurocognitive domains. There was significant heterogeneity across studies for the neurocognitive domains of global cognition, executive functions, as well as learning and memory. Visual inspection of funnel plots as well as Egger's test revealed no significant funnel plot asymmetry for any of the neurocognitive domains, indicating no publication biases. Therefore, sensitivity analyses using the trim and fill method for random effects models were not necessary.

Table 2 presents all the results of the moderator analyses. In summary, body position significantly moderated the effectiveness of exergame-based training on global cognition ($Q_M(df = 2) = 5.99$, $p = 0.05$), favoring step-based exergame training over exergaming in a standing position with mainly weight shifting and exergaming in a sitting position. This variable explained approximately 36 % of the variance in effect sizes across studies. Significant moderators of complex attention included type of motor-cognitive training ($Q_M(df = 1) = 3.78$, $p = 0.05$), training location ($Q_M(df = 2) = 9.02$, $p = 0.01$), and training administration ($Q_M(df = 1) = 6.79$, $p = 0.01$), favoring simultaneous-incorporated motor-cognitive training, a combination of training at home and on-site training, and group training. In addition, fully supervised training tended to be more effective, with supervision of training being borderline significant as a moderator variable ($Q_M(df = 2) = 5.19$, $p = 0.07$). For executive functions, exercise intensity was a significant moderator ($Q_M(df = 2) = 5.86$, $p = 0.05$), favoring a moderate exercise intensity over light or vigorous exercise intensities. This variable explained approximately 86 % of the variance in effect sizes across studies.

The planned subgroup and sensitivity analyses revealed no differences in the effectiveness of exergame-based training in relation to the type of population, cognitive status, methodological quality, or adherence to training in any of the neurocognitive domains.

4. Discussion

This study aimed to investigate dose-response relationships of specific exercise and training variables (training components) of exergame-based training on cognitive performance in MOA through a meta-analysis of the current state of the literature. Elucidating such dose-response relationships is an important step to develop evidence-based recommendations for the optimal training components of exergame-based training to improve cognitive functioning in MOA. We found that exergame-based training was effective in improving the neurocognitive domains of global cognition, complex attention, and executive functions, but not learning and memory or visuospatial skills. The effectiveness of exergame-based training on global cognition was moderated by body position, while the effectiveness on complex attention was moderated by the type of motor-cognitive training, training

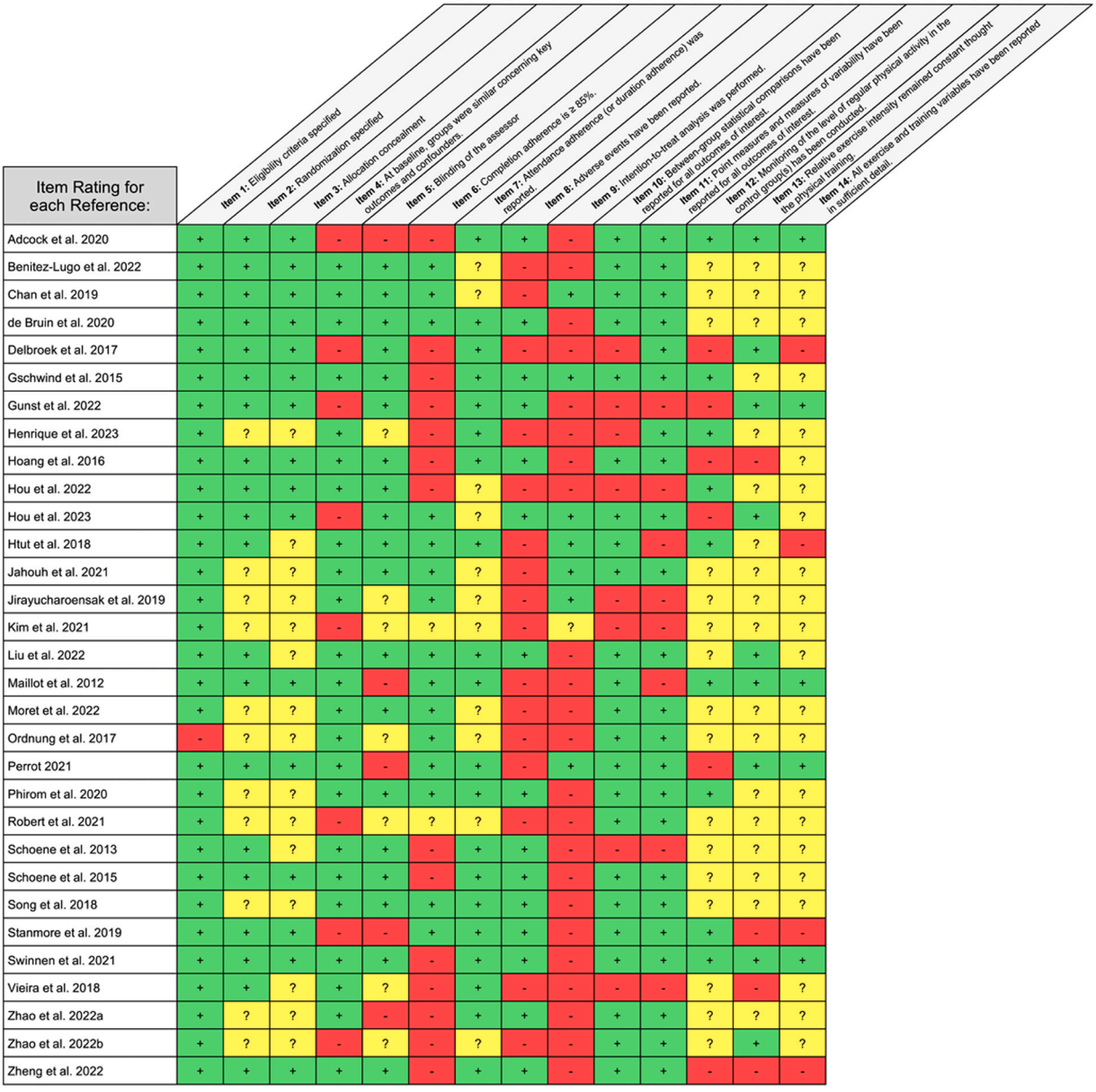


Fig. 2. Rating of the modified version (Herold et al., 2023) of the Tool for the Assessment of Study Quality and Reporting in Exercise scale (Smart et al., 2015).

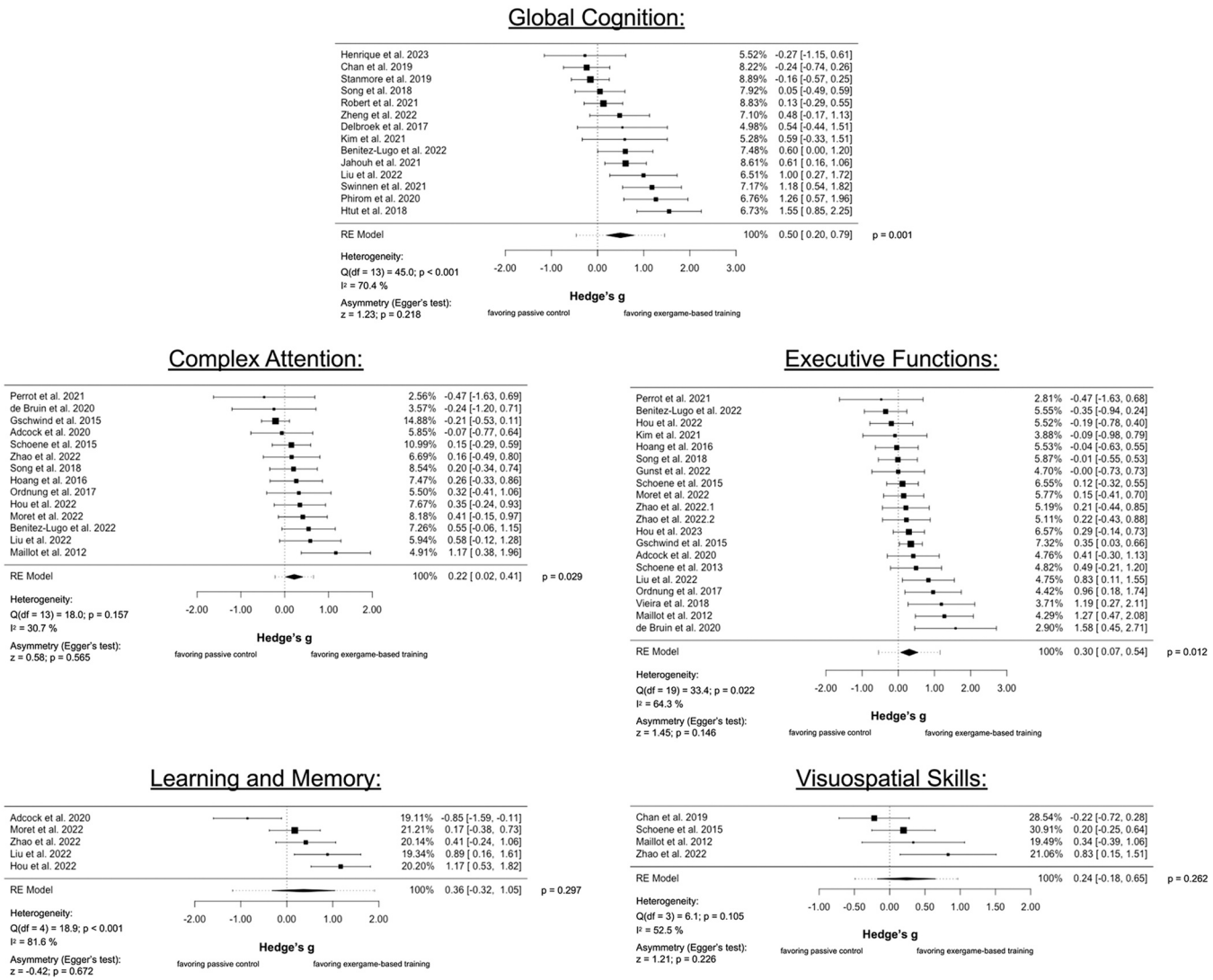


Fig. 3. Forest Plots for the meta-analyses for each neurocognitive domain. FE; fixed effects.

location, and training administration, and the effectiveness on executive functions was moderated by exercise intensity.

4.1. *Principal findings*

4.1.1. *Body position as a moderator of effectiveness*

Our finding that body position moderated the effectiveness of exergame-based training on global cognition, favoring step-based exergame training over exergaming in a standing position with mainly weight shifting and exergaming in a sitting position, is significant and novel. Notably, our findings are derived from a moderator analysis, providing quantitative insights that extend similar findings derived from the qualitative synthesis of two previous literature reviews (Di Lorito et al., 2022; Manser and de Bruin, 2021). Di Lorito et al. (2022) investigated the effectiveness of digital health interventions in individuals with mild to major neurocognitive disorder. They observed that studies with stepping exergames had the largest effect sizes on physical and cognitive performance (Di Lorito et al., 2022). Our group conducted a qualitative synthesis of the evidence on the moderating effects of different physical and cognitive training types and components in individuals with mild neurocognitive disorder. The findings suggested that exercise should be performed in a vertical body loading position that requires a changing base of support (Manser and de Bruin, 2021).

Our results might be explained by the findings of Tahmosybayat et al. (2018), who observed that exergames performed in a standing position, involving stepping and whole-body movements outside the base of support, better fulfill the requirements for training postural control (Tahmosybayat et al., 2018). Because cognitive functioning and the control of complex motor tasks are functionally related (e.g., by sharing a common set of neural substrates) (Leisman et al., 2016), the concomitantly higher motoric task demands of step-based exergame training probably pose higher demands on cognitive processes as compared to exergames including only weight shifting or sitting (Dodwell et al., 2019) and might provide a more ecologically valid training approach, which is in line with the predictions of the Ecological Validity Assessment Tool (ECOVAL) and its theoretical assumptions (Chang et al., 2022). Accordingly, exergame-based training including ecologically more valid conditions (i.e., step-based and whole-body movements in a standing position) might provide more pronounced stimuli for adaptations of cognitive functioning compared to exergaming with solely weight shifting or performed in a sitting position. To confirm these findings, specific comparisons of exergame-based training involving stepping and whole-body movements outside the base of support with exergames involving solely weight shifting, exergames played in sitting position, and/or videogames played in sitting position with otherwise identical training conditions and game contents are required. However, only one of the reviewed studies, namely Hou et al. (2022), investigated the effects of different body positions on intervention-related changes of

cognitive performance in older adults (Hou and Li, 2022). In particular, Hou et al. (2022) compared two interventions in older adults, a step-based exergame training and a seated video game training, with otherwise identical training conditions and game content, to an inactive control group. They observed significant improvements in multiple domains of cognitive and physical functioning in both intervention groups. However, the effects were consistently greater for the exergame-based training group (Hou and Li, 2022), providing preliminary evidence that further supports our finding and underscores the importance of the body position as a critical factor which should be considered when aiming to optimize cognitive outcomes in MOA through simultaneous motor-cognitive interventions such as exergames. Based on the limited number of studies that have evaluated exergaming in a seated position or focused on weight shifting while standing, the available data and our analyses did not support the same conclusions for the other evaluated neurocognitive domains (i.e., learning and memory, complex attention,

Table 2
Results of the Moderator Analysis.

Font coding: black-normal = statistical results of non-significant moderators and/or statistical results of subgroups of significant moderators
black-bold = statistical results of significant moderators and/or statistical results of subgroups of significant moderators
grey-normal = non-significant statistical results of subgroups of non-significant moderators
grey-bold = significant statistical results of subgroups of non-significant moderators

Abbreviations: $CI_{95\,\%}$, 95 % confidence intervals; df, degrees of freedom; k, number of studies; N, total analyzed sample size; p, p-value; Q_M, Cochrane's Q of the model;

	Moderator	Test of Moderators		
	Variable of interest (and pre-specified subgroups)	Global Cognition	Complex Attention	Executive Functions
Population	**Type of population:**	Q_M(df = 1) = 0.18, p = 0.67	Q_M(df = 1) = 0.05, p = 0.82	Q_M(df = 1) = 0.12, p = 0.73
	healthy middle-aged to older adults	**Hedge's g = 0.58, $CI_{95\%}$ [0.09 – 1.07], p = 0.02, k = 6, N = 229**	**Hedge's g = 0.23, $CI_{95\%}$ [0.00 – 0.46], p = 0.05, k = 9, N = 509**	Hedge's g = 0.27, $CI_{95\%}$ [-0.04 – 0.58], p = 0.08, k = 12, N = 598
	middle-aged to older adults with clinical condition(s)	**Hedge's g =0.44, $CI_{95\%}$ [0.04 – 0.84], p = 0.03, k = 8, N = 449**	Hedge's g = 0.18, $CI_{95\%}$ [-0.19 – 0.55], p = 0.33, k = 5, N = 159	Hedge's g = 0.36, $CI_{95\%}$ [-0.04 – 0.76], p = 0.08, k = 8, N = 294
	Cognitive Status:	Q_M(df = 1) = 0.00, p = 0.98	Q_M(df = 1) = 0.01, p = 0.93	Q_M(df = 1) = 0.83, p = 0.36
	healthy	**Hedge's g = 0.49, $CI_{95\%}$ [0.05 – 0.94], p = 0.03, k = 7, N = 282**	**Hedge's g = 0.22, $CI_{95\%}$ [0.00 – 0.44], p = 0.05, k = 12, N = 623**	**Hedge's g = 0.26, $CI_{95\%}$ [0.01 – 0.52], p = 0.05, k = 17, N = 825**
	cognitively impaired	**Hedge's g = 0.50, $CI_{95\%}$ [0.07 – 0.93], p = 0.02, k = 7, N = 396**	Hedge's g = 0.26, $CI_{95\%}$ [-0.44 – 0.95], p = 0.47, k = 2, N = 45	Hedge's g = 0.62, $CI_{95\%}$ [-0.10 – 1.34], p = 0.09, k = 3, N = 67
Basic Exercise Variables	**Type of motor-cognitive training:**	Q_M(df = 1) = 0.02, p = 0.89	**Q_M(df = 1) = 3.78, p = 0.05**	Q_M(df = 1) = 0.10, p = 0.75
	simultaneous-incorporated	**Hedge's g = 0.49, $CI_{95\%}$ [0.17 – 0.82], p < 0.01, k = 13, N = 658**	**Hedge's g = 0.29, $CI_{95\%}$ [0.09 – 0.50], p < 0.01, k = 13, N = 515**	**Hedge's g = 0.32, $CI_{95\%}$ [0.06 – 0.58], p = 0.02, k = 18, N = 719**
	simultaneous-additional	Hedge's g = 0.59, $CI_{95\%}$ [-0.76 – 1.94], p = 0.39, k = 1, N = 20	Hedge's g = -0.21, $CI_{95\%}$ [-0.67 – 0.26], p = 0.38, k = 1, N = 153	Hedge's g = 0.19, $CI_{95\%}$ [-0.53 – 0.92], p = 0.60, k = 2, N = 173
	Exercise Intensity:	Q_M(df = 1) = 0.45, p = 0.50	Q_M(df = 1) = 1.75, p = 0.39	**Q_M(df = 2) = 5.86, p = 0.05**
	light	Hedge's g = 0.48, $CI_{95\%}$ [-0.26 – 1.22], p = 0.21, k = 3, N = 154	Hedge's g = 0.03, $CI_{95\%}$ [-0.74 – 0.80], p = 0.94, k = 2, N = 56	Hedge's g = -0.09, $CI_{95\%}$ [-0.56 – 0.37], p = 0.69, k = 3, N = 85
	moderate	Hedge's g = 0.10, $CI_{95\%}$ [-0.32 – 2.31], p = 0.14, k = 1, N = 33	Hedge's g = 0.44, $CI_{95\%}$ [-0.07 – 0.94], p = 0.09, k = 4, N = 132	**Hedge's g = 0.58, $CI_{95\%}$ [0.28 – 0.87], p < 0.01, k = 6, N = 238**
	vigorous	N/A	N/A	Hedge's g = 0.22, $CI_{95\%}$ [-0.49 – 0.94], p = 0.54, k = 1, N = 37
	Exercise Duration:	Q_M(df = 3) = 0.94, p = 0.82	Q_M(df = 3) = 0.48, p = 0.92	Q_M(df = 3) = 3.79, p = 0.29
	≤ 15 min / per session	Hedge's g = 0.31, $CI_{95\%}$ [-0.22 – 0.83], p = 0.25, k = 5, N = 319	Hedge's g = 0.06, $CI_{95\%}$ [-0.56 – 0.68], p = 0.86, k = 2, N = 70	Hedge's g = 0.50, $CI_{95\%}$ [-0.27 – 1.26], p = 0.21, k = 2, N = 70
	> 15 to ≤ 30 min / session	**Hedge's g = 0.58, $CI_{95\%}$ [0.01 – 1.30], p = 0.05, k = 5, N = 187**	Hedge's g = 0.31, $CI_{95\%}$ [-0.07 – 0.69], p = 0.11, k = 4, N = 215	Hedge's g = -0.02, $CI_{95\%}$ [-0.42 – 0.39], p = 0.94, k = 6, N = 267
	> 30 to ≤ 45 min / session	Hedge's g = 0.61, $CI_{95\%}$ [-0.53 – 1.74], p = 0.30, k = 1, N = 80	Hedge's g = 0.21, $CI_{95\%}$ [-0.37 – 0.79], p = 0.48, k = 2, N = 88	Hedge's g = 0.27, $CI_{95\%}$ [-0.43 – 0.97], p = 0.45, k = 2, N = 88
	> 45 min / session	Hedge's g = 0.71, $CI_{95\%}$ [-0.04 – 1.46], p = 0.06, k = 3, N = 92	Hedge's g = 0.22, $CI_{95\%}$ [-0.13 – 0.57], p = 0.21, k = 6, N = 295	**Hedge's g = 0.48, $CI_{95\%}$ [0.15 – 0.80], p < 0.01, k = 10, N = 467**
Basic Training Variables	**Training Frequency:**	Q_M(df = 2) = 0.71, p = 0.70	Q_M(df = 1) = 1.87, p = 0.17	Q_M(df = 1) = 0.41, p = 0.52
	≤ 2x/week	Hedge's g = 0.31, $CI_{95\%}$ [-0.24 – 0.86], p = 0.27, k = 5, N = 194	**Hedge's g = 0.44, $CI_{95\%}$ [0.07 – 0.82], p = 0.02, k = 5, N = 161**	Hedge's g = 0.19, $CI_{95\%}$ [-0.24 – 0.61], p = 0.39, k = 7, N = 210
	3x/week	**Hedge's g = 0.60, $CI_{95\%}$ [0.20 – 1.00], p < 0.01, k = 8, N = 446**	Hedge's g = 0.13, $CI_{95\%}$ [-0.01 – 0.37], p = 0.26, k = 9, N = 507	Hedge's g = 0.36, $CI_{95\%}$ [0.07 – 0.64], p = 0.02, k = 13, N = 682
	≥ 4x/week	Hedge's g = 0.48, $CI_{95\%}$ [-0.69 – 1.64], p = 0.42, k = 1, N = 38	N/A	N/A
	Training Density:	N/A (all studies in category 'between-session recovery time ≥ 24 h but < 48 h')	Q_M(df = 1) = 0.12, p = 0.73	Q_M(df = 1) = 0.01, p = 0.92
	between-session recovery time < 24 h	N/A	N/A	N/A
	between-session recovery time ≥ 24 h but < 48 h	N/A	Hedge's g = -0.07, $CI_{95\%}$ [-2.22 – 2.09], p = 0.95, k = 1, N = 31	Hedge's g = 0.41, $CI_{95\%}$ [-1.26 – 2.09], p = 0.63, k = 1, N = 31
	between-session recovery time ≥ 48 h	N/A	Hedge's g = 0.41, $CI_{95\%}$ [-1.19 – 2.01], p = 0.62, k = 2, N = 42	Hedge's g = 0.31, $CI_{95\%}$ [-0.70 – 1.33], p = 0.55, k = 2, N = 71
	Training Duration:	Q_M(df = 1) = 0.20, p = 0.66	Q_M(df = 3) = 3.57, p = 0.31	Q_M(df = 3) = 0.97, p = 0.81
	≤ 4 weeks	N/A	Hedge's g = 0.21, $CI_{95\%}$ [-0.38 – 0.79], p = 0.49, k = 2, N = 74	Hedge's g = 0.64, $CI_{95\%}$ [-0.19 – 1.46], p = 0.13, k = 2, N = 74
	5 - 8 weeks	**Hedge's g = 0.56, $CI_{95\%}$ [0.15 – 0.97], p = 0.01, k = 8, N = 350**	Hedge's g = 0.45, $CI_{95\%}$ [-0.11 – 1.01], p = 0.12, k = 2, N = 75	Hedge's g = 0.32, $CI_{95\%}$ [-0.31 – 0.95], p = 0.32, k = 3, N = 107
	9 - 12 weeks	Hedge's g = 0.42, $CI_{95\%}$ [-0.05 – 0.89], p = 0.08, k = 6, N = 328	**Hedge's g = 0.35, $CI_{95\%}$ [0.05 – 0.66], p = 0.02, k = 7, N = 254**	Hedge's g = 0.20, $CI_{95\%}$ [-0.17 – 0.57], p = 0.29, k = 9, N = 311
	≥ 13 weeks	N/A	Hedge's g = -0.06, $CI_{95\%}$ [-0.42 – 0.31], p = 0.77, k = 3, N = 265	Hedge's g = 0.35, $CI_{95\%}$ [-0.07 – 0.77], p = 0.11, k = 6, N = 400

(*continued on next page*)

Table 2 (*continued*)

Other Training Components	**Training Volume (weekly):**	Q_M(df = 3) = 2.27, p = 0.52	Q_M(df = 2) = 0.33, p = 0.85	Q_M(df = 3) = 3.81, p = 0.28
	< 60 min	Hedge's g = 0.33, $CI_{95\%}$ [-0.13 – 0.79], p = 0.16, k = 6, N = 336	Hedge's g = 0.06, $CI_{95\%}$ [-0.53 – 0.66], p = 0.84, k = 2, N = 70	Hedge's g = 0.49, $CI_{95\%}$ [-0.12 – 1.11], p = 0.12, k = 3, N = 102
	60 - 119 min	**Hedge's g = 0.59, $CI_{95\%}$ [0.08 – 1.10], p = 0.02, k = 5, N = 250**	Hedge's g = 0.25, $CI_{95\%}$ [-0.08 – 0.59], p = 0.14, k = 5, N = 246	Hedge's g = -0.03, $CI_{95\%}$ [-0.43 – 0.37], p = 0.89, k = 6, N = 266
	120 - 179 min	Hedge's g = 0.41, $CI_{95\%}$ [-0.47 – 1.30], p = 0.36, k = 2, N = 53	Hedge's g = 0.24, $CI_{95\%}$ [-0.06 – 0.55], p = 0.11, k = 7, N = 352	**Hedge's g = 0.43, $CI_{95\%}$ [0.07 – 0.79], p = 0.02, k = 8, N = 381**
	≥ 180 min	**Hedge's g = 1.26, $CI_{95\%}$ [0.08 – 2.45], p = 0.04, k = 1, N = 39**	N/A	Hedge's g = 0.48, $CI_{95\%}$ [-0.10 – 1.06], p = 0.10, k = 3, N = 143
	Training Volume (in total):	Q_M(df = 2) = 2.97, p = 0.23	Q_M(df = 3) = 3.00, p = 0.39	Q_M(df = 3) = 0.46, p = 0.93
	< 1,000 min	**Hedge's g = 0.40, $CI_{95\%}$ [0.09 – 0.71], p = 0.01, k = 12, N = 606**	Hedge's g = 0.26, $CI_{95\%}$ [-0.03 – 0.56], p = 0.08, k = 7, N = 327	Hedge's g = 0.24, $CI_{95\%}$ [-0.15 – 0.62], p = 0.23, k = 9, N = 379
	1,000 - 1,499 min	N/A	Hedge's g = 0.47, $CI_{95\%}$ [-0.06 – 1.00], p = 0.08, k = 3, N = 86	Hedge's g = 0.24, $CI_{95\%}$ [-0.82 – 0.80], p = 0.98, k = 3, N = 86
	1,500 - 2,000 min	Hedge's g = 0.10, $CI_{95\%}$ [-0.14 to 2.13], p = 0.09, k = 1, N = 33	Hedge's g = 0.22, $CI_{95\%}$ [-0.26 – 0.71], p = 0.36, k = 3, N = 102	Hedge's g = 0.36, $CI_{95\%}$ [-0.22 – 0.94], p = 0.22, k = 4, N = 131
	≥ 2,000 min	**Hedge's g = 1.26, $CI_{95\%}$ [0.15 – 2.38], p = 0.03, k = 1, N = 39**	Hedge's g = -0.21, $CI_{95\%}$ [-0.79 – 0.38], p = 0.48, k = 1, N = 153	Hedge's g = 0.45, $CI_{95\%}$ [-0.10 – 0.99], p = 0.11, k = 4, N = 296
	Training Location:	Q_M(df = 1) = 0.19, p = 0.67	**Q_M(df = 2) = 9.02, p = 0.01**	Q_M(df = 1) = 3.94, p = 0.14
	at home	Hedge's g = 0.75, $CI_{95\%}$ [-0.06 – 1.55], p = 0.07, k = 2, N = 95	Hedge's g = 0.02, $CI_{95\%}$ [-0.18 – 0.21], p = 0.87, k = 6, N = 400	Hedge's g = 0.29, $CI_{95\%}$ [-0.06 – 0.65], p = 0.10, k = 8, N = 454
	at study or training center, clinic, or similar	**Hedge's g = 0.55, $CI_{95\%}$ [0.15 – 0.94], p = 0.01, k = 8, N = 448**	Hedge's g = 0.30, $CI_{95\%}$ [-0.01 – 0.61], p = 0.06, k = 5, N = 176	Hedge's g = 0.07, $CI_{95\%}$ [-0.34 – 0.48], p = 0.75, k = 7, N = 242
	mixed approaches	N/A	**Hedge's g = 1.17, $CI_{95\%}$ [0.38 – 1.96], p < 0.01, k = 1, N = 30**	**Hedge's g = 1.27, $CI_{95\%}$ [0.14 – 2.41], p = 0.03, k = 1, N = 30**
	Training Administration:	Q_M(df = 2) = 0.83, p = 0.66	**Q_M(df = 1) = 6.79, p = 0.01**	Q_M(df = 1) = 0.31, p = 0.58
	performed individually	**Hedge's g = 0.70, $CI_{95\%}$ [0.18 – 1.22], p = 0.01, k = 6, N = 288**	Hedge's g = 0.05, $CI_{95\%}$ [-0.14 – 0.23], p = 0.61, k = 8, N = 469	Hedge's g = 0.23, $CI_{95\%}$ [-0.05 – 0.52], p = 0.11, k = 10, N = 523
	performed in a group	Hedge's g = 0.73, $CI_{95\%}$ [-0.18 – 1.64], p = 0.12, k = 2, N = 71	**Hedge's g = 0.62, $CI_{95\%}$ [0.23 – 1.01], p < 0.01, k = 3, N = 107**	Hedge's g = 0.38, $CI_{95\%}$ [-0.05 – 0.81], p = 0.08, k = 5, N = 173
	mixed approaches	Hedge's g = 0.127, $CI_{95\%}$ [-1.039 – 1.293], p = 0.831, k = 1, N = 91	N/A	N/A
	Supervision of Training:	Q_M(df = 1) = 1.14, p = 0.28	Q_M(df = 2) = 5.19, p = 0.07	Q_M(df = 2) = 0.16, p = 0.92
	fully supervised	**Hedge's g = 0.61, $CI_{95\%}$ [0.27 – 0.94], p < 0.01, k = 9, N = 484**	**Hedge's g = 0.47, $CI_{95\%}$ [0.18 – 0.76], p < 0.01, k = 7, N = 251**	Hedge's g = 0.27, $CI_{95\%}$ [-0.05 – 0.59], p = 0.10, k = 10, N = 401
	partially supervised	Hedge's g = 0.05, $CI_{95\%}$ [-0.91 – 1.02], p = 0.92, k = 1, N = 53	Hedge's g = -0.07, $CI_{95\%}$ [-0.45 – -0.32], p = 0.74, k = 2, N = 206	Hedge's g = 0.19, $CI_{95\%}$ [-0.42 – 0.80], p = 0.54, k = 2, N = 206
	unsupervised	N/A	Hedge's g = 0.14, $CI_{95\%}$ [-0.20 – 0.48], p = 0.42, k = 4, N = 194	Hedge's g = 0.33, $CI_{95\%}$ [-0.07 – 0.74], p = 0.11, k = 6, N = 248
	Individualization of Training:	Q_M(df = 1) = 0.06, p = 0.80	Q_M(df = 1) = 0.63, p = 0.43	Q_M(df = 1) = 0.05, p = 0.82
	tailored	**Hedge's g = 0.65, $CI_{95\%}$ [0.21 – 1.09], p < 0.01, k = 8, N = 412**	Hedge's g = 0.17, $CI_{95\%}$ [-0.11 – 0.45], p = 0.24, k = 8, N = 490	**Hedge's g = 0.29, $CI_{95\%}$ [0.04 – 0.55], p = 0.02, k = 12, N = 665**
	generic (one size fits all)	Hedge's g = 0.48, $CI_{95\%}$ [-0.77 – 1.73], p = 0.45, k = 1, N = 38	Hedge's g = 0.43, $CI_{95\%}$ [-0.14 – 1.00], p = 0.14, k = 3, N = 86	Hedge's g = 0.23, $CI_{95\%}$ [-0.29 – 0.74], p = 0.39, k = 4, N = 115
	Specificity of Training:	Q_M(df = 2) = 1.86, p = 0.40	Q_M(df = 1) = 0.22, p = 0.64	Q_M(df = 1) = 2.36, p = 0.12
	neurocognitive functioning	**Hedge's g = 0.58, $CI_{95\%}$ [0.25 – 0.91], p < 0.01, k = 11, N = 533**	Hedge's g = 0.27, $CI_{95\%}$ [-0.01 – 0.55], p = 0.06, k = 7, N = 342	Hedge's g = 0.11, $CI_{95\%}$ [-0.24 – 0.45], p = 0.55, k = 9, N = 394
	multicomponent	Hedge's g = 0.33, $CI_{95\%}$ [-0.43 – 1.09], p = 0.39, k = 2, N = 125	Hedge's g = 0.17, $CI_{95\%}$ [-0.13 – 0.47], p = 0.27, k = 7, N = 326	**Hedge's g = 0.47, $CI_{95\%}$ [0.15 – 0.79], p < 0.01, k = 11, N = 498**
	strength	Hedge's g = -0.273, $CI_{95\%}$ [-1.536 – 0.990], p = 0.200, k = 1, N = 20	N/A	N/A
	Body Position during Training:	**Q_M(df = 2) = 5.99, p = 0.05**	Q_M(df = 2) = 0.75, p = 0.39	Q_M(df = 1) = 1.97, p = 0.37
	standing - stepping incl. weight shifting	**Hedge's g = 0.76, $CI_{95\%}$ [0.40 – 1.11], p < 0.01, k = 7, N = 383**	Hedge's g = 0.19, $CI_{95\%}$ [-0.03 – 0.42], p = 0.10, k = 12, N = 593	**Hedge's g = 0.33, $CI_{95\%}$ [0.06 – 0.60], p = 0.02, k = 16, N = 713**
	standing - mainly weight shifting	Hedge's g = 0.06, $CI_{95\%}$ [-0.38 – 0.49], p = 0.79, k = 5, N = 237	Hedge's g = 0.55, $CI_{95\%}$ [-0.23 – 1.32], p = 0.17, k = 1, N = 46	Hedge's g = -0.35, $CI_{95\%}$ [-1.37 – 0.67], p = 0.50, k = 1, N = 46
	sitting	Hedge's g = 0.52, $CI_{95\%}$ [-0.23 – 1.27], p = 0.17, k = 2, N = 58	N/A	Hedge's g = -0.09, $CI_{95\%}$ [-0.31 – 1.13], p = 0.88, k = 1, N = 20
	Design of Exergames:	Q_M(df = 1) = 0.79, p = 0.37	Q_M(df = 1) = 0.20, p = 0.65	Q_M(df = 1) = 0.01, p = 0.92
	serious games	**Hedge's g = 0.62, $CI_{95\%}$ [0.29 – 0.95], p < 0.01, k = 11, N = 525**	Hedge's g = 0.18, $CI_{95\%}$ [-0.11 – 0.46], p = 0.22, k = 6, N = 401	Hedge's g = 0.29, $CI_{95\%}$ [-0.09 – 0.66], p = 0.13, k = 8, N = 443
	recreational games	Hedge's g = 0.25, $CI_{95\%}$ [-0.48 – 0.99], p = 0.50, k = 2, N = 91	Hedge's g = 0.27, $CI_{95\%}$ [-0.03 – 0.57], p = 0.07, k = 8, N = 267	Hedge's g = 0.32, $CI_{95\%}$ [-0.01 – 0.64], p = 0.06, k = 12, N = 449
	Level of Cognitive Demand:	N/A (not determined or assessed by any of the included studies)	N/A (not determined or assessed by any of the included studies)	N/A (not determined or assessed by any of the included studies)
Adherence	**Attendance Adherence:**	Q_M(df = 2) = 2.29, p = 0.32	Q_M(df = 2) = 0.00, p = 0.99	Q_M(df = 2) = 0.39, p = 0.42
	> 85 %	**Hedge's g = 0.80, $CI_{95\%}$ [0.28 – 1.32], p < 0.01, k = 6, N = 222**	Hedge's g = 0.16, $CI_{95\%}$ [-0.15 – 0.46], p = 0.30, k = 9, N = 411	**Hedge's g = 0.39, $CI_{95\%}$ [0.04 – 0.74], p = 0.03, k = 11, N = 472**
	≥ 75 - 85 %	Hedge's g = 0.53, $CI_{95\%}$ [-0.39 – 1.45], p = 0.26, k = 2, N = 65	N/A	Hedge's g = 1.19, $CI_{95\%}$ [-0.10 – 2.49], p = 0.07, k = 1, N = 22
	< 75 %	Hedge's g = -0.16, $CI_{95\%}$ [-1.30 – 0.98], p = 0.79, k = 1, N = 92	Hedge's g = 0.15, $CI_{95\%}$ [-0.60 – 0.91], p = 0.69, k = 1, N = 81	Hedge's g = 0.12, $CI_{95\%}$ [-0.89 – 1.12], p = 0.82, k = 1, N = 81
Quality	**Study Quality:**	Q_M(df = 1) = 1.32, p = 0.25	Q_M(df = 1) = 0.96, p = 0.33	Q_M(df = 1) = 0.94, p = 0.33
	≤ 5 items with unclear or high risk of bias	**Hedge's g = 0.66, $CI_{95\%}$ [0.26 – 1.06], p < 0.01, k = 7, N = 351**	Hedge's g = 0.13, $CI_{95\%}$ [-0.13 – 0.40], p = 0.33, k = 8, N = 401	**Hedge's g = 0.43, $CI_{95\%}$ [0.08 – 0.78], p = 0.02, k = 9, N = 485**
	> 5 items with unclear or high risk of bias	Hedge's g = 0.32, $CI_{95\%}$ [-0.09 – 0.73], p = 0.13, k = 7, N = 327	**Hedge's g = 0.33, $CI_{95\%}$ [0.03 – 0.63], p = 0.03, k = 6, N = 267**	Hedge's g = 0.20, $CI_{95\%}$ [-0.13 – 0.52], p = 0.23, k = 11, N = 407

executive function, and visuospatial skills). Therefore, further neuroscientific research is warranted to reveal the influence of body position during the exergame-based training on the effectiveness to improve cognitive functioning and elucidate its biological mechanisms driving the superior effects of step-based exergames with whole-body movements in a standing position on cognitive performance in MOA as compared to exergames conducted in other body positions (e.g., standing with solely weight shifting or sitting). Nonetheless, based on the current evidence it seems plausible to propose that future research should utilize ecologically more valid conditions (e.g., step-based and whole-body movements in a standing position) to facilitate the effectiveness of (exergame-based) simultaneous motor-cognitive training. We strongly recommend that this factor should be considered in addition to the recommendations provided by Torre and Temprado (2022) (Torre and Temprado, 2022a) as well as our previous recommendations (Manser and de Bruin, 2021) when moving forward to establish a scientific consensus on the optimal exergame-based training components to improve cognitive functioning in MOA.

4.1.2. *Type of motor-cognitive training as a moderator of effectiveness*

Our findings suggest that exergame-based training which can be classified as simultaneous-incorporated motor-cognitive training was more effective in improving complex attention than exergame-based training interventions which can be categorized as simultaneous-additional (dual-task) motor-cognitive training. This observation provides further empirical evidence for the assumptions outlined in the 'guided plasticity facilitation' framework (Fabel and Kempermann, 2008; Herold et al., 2018; Kempermann et al., 2010), which predicts that incorporating cognitive tasks into motor tasks is more beneficial in terms of stabilizing neuroplasticity effects compared to dual-task training. According to the 'guided plasticity facilitation' framework (Fabel and Kempermann, 2008; Herold et al., 2018; Kempermann et al., 2010) and in line with the ECOVAL (Chang et al., 2022), simultaneous-incorporated motor-cognitive training that incorporates multiple sensory systems provides higher ecological validity than dual-task training. An intervention with a higher ecological validity (i.e., simultaneous-incorporated motor-cognitive training that incorporates multiple sensory systems), in turn, might enhance expectations (beliefs toward the effectiveness of the intervention) and preferences to engage in the training, which can promote training adherence that is known to positively moderate training effectiveness (Herold et al., 2018). An additional advantage of simultaneous-incorporated motor-cognitive training is that no prioritization effects occur as opposed to dual-task training (Herold et al., 2018). To the best of our knowledge, our analysis was the first of its kind providing meta-analytic evidence supporting the prediction of the 'guided plasticity facilitation' framework in MOA (Fabel and Kempermann, 2008; Herold et al., 2018; Kempermann et al., 2010). Notably, previous meta-analyses have found superiority of simultaneous over sequential motor-cognitive training (Rieker et al., 2022), no significant difference between these two training types (Gavelin et al., 2021), or mixed findings concerning the improvement of cognitive performance in the aging population, depending on the neurocognitive domain that was assessed (Zhao et al., 2022). However, these above-mentioned meta-analyses did not distinguish between simultaneous-incorporated and simultaneous-additional motor-cognitive training.

Our findings need to be interpreted with caution due to the small number of exergame-based studies applying simultaneous-additional motor-cognitive training and do not allow generalization to other neurocognitive domains than complex attention. Nonetheless, when only considering the exergame-based studies applying simultaneous-incorporated motor-cognitive training, consistent and statistically significant positive effects were found for all investigated neurocognitive domains. Therefore, although further investigations are required to substantiate our observation, our findings support exergame-based training that implements simultaneous-incorporated over simultaneous-additional motor-cognitive training, as proposed by Torre and Temprado (2022) (Torre and Temprado, 2022a) and our group (Manser and de Bruin, 2021).

4.1.3. *Exercise intensity as a moderator of effectiveness*

Although it has been reported that (commercial) exergames may not allow reaching high enough levels of physical exercise intensity (Temprado and Torre, 2022), we identified several studies that implemented moderate or even a vigorous levels of physical exercise intensity and found that a moderate exercise intensity was favorable to improve executive functions, which is consistent with previous findings for conventional training (Biazus-Sehn et al., 2020; Law et al., 2020). This observation suggests that a certain level of physical exercise intensity is required to stimulate the "facilitation effect" of physical exercise. The facilitation effect describes the promotion of synaptogenesis, neurogenesis, and angiogenesis through neurophysiological mechanisms induced by physical exercise. These include the direct release of brain-derived neurotrophic factor, insulin-like growth factor-1, and vascular endothelial growth factor in the brain, as well as an increase in circulating biomolecules irisin and cathepsin B from skeletal muscle. (Fabel and Kempermann, 2008; Herold et al., 2018; Huuha et al., 2022; Kempermann et al., 2010) In line with this potential explanation, preliminary evidence from systematic reviews suggests that at least a moderate exercise intensity may be required to sufficiently stimulate the release of these neurotrophic factors (Ashcroft et al., 2022; da Cunha et al., 2023; García-Hermoso et al., 2023; Jemni et al., 2023; Rotondo et al., 2023; Sivaramakrishnan and Subramanian, 2023; Wang et al., 2022). However, a key limitation of our analysis on exercise intensity was that we were only able to include 41.9 % of the reviewed studies in this moderator analysis because the remaining studies did not provide sufficient information to rate the exercise intensity although this information was repeatedly requested from author teams. Thus, our data should be interpreted in light of this limitation. Additionally, our data did not allow generalization to other neurocognitive domains than executive functions. Nonetheless, our findings partly support the recommendation for a moderate exercise intensity as proposed by Torre and Temprado (2022) (Torre and Temprado, 2022a) and our group (Manser and de Bruin, 2021).

4.1.4. *Training location, administration, and supervision as moderators of effectiveness*

Our results indicate that group-based training is most effective for improving complex attention, while fully supervised training tends to be more effective for improving complex attention. These observations are consistent with the evidence on conventional motor-cognitive training (Rieker et al., 2022). In particular, Rieker et al. (2022) found that combined motor-cognitive training performed in a group setting was associated with more pronounced improvements in cognitive performance as compared to training performed individually (without supervision) in older adults (Rieker et al., 2022). The authors explained this observation by the social interaction, which served as an important motivational factor for the training (Rieker et al., 2022), and which is known to contribute to the preservation of the cognitive functioning via several not fully understood psychological and biological mechanisms (Sommerlad et al., 2023). Furthermore, supervision may serve as a mediating mechanism to enhancing participant engagement and training adherence (Di Lorito et al., 2022) which is, in turn, mirrored in the observed more pronounced intervention-related changes in complex attention in our sample of MOA. Moreover, supervised group training more accurately resembles participation in real-world training settings and therefore has higher ecological validity according to ECOVAL (Chang et al., 2022). Finally, these findings also support the predictions of the 'Optimizing Performance through Intrinsic Motivation and Attention for Learning (OPTIMAL)' theory of motor learning (Wulf and Lewthwaite, 2016), particularly in terms of the role of social factors (i.e., the presence of one or more other persons can provide reassurance for

good performance and can exert a facilitating influence.), which promotes enhanced expectancies (i.e., circumstances that enhance learners' expectations of future performance success that can potentiate even more success, improvement, and learning by triggering a higher dopamine release that probably foster processes of memory consolidation and neural pathway development), autonomy support (i.e., the need to actively participate in determining one's own behavior which facilitates performance by enhancing expectancies), external focus of attention (i.e., a concentration on the intended movement effect which directs attention to the task goal, enhancing goal-action coupling), and the interplay between challenge and dopaminergic response in facilitating motor learning and performance (i.e., challenge, in the context of prevailing success, elicits a potentiating dopaminergic response that contributes to learning beyond success or challenge alone). (Wulf and Lewthwaite, 2016)

Previous research suggested that a combination of remote and face-to-face delivery of training could maximize benefits and optimize costs (Di Lorito et al., 2022) while all sessions should be supervised by experienced and specialized coaches (Torre and Temprado, 2022a). This is in line with our findings, although they must be interpreted with caution because only one of the included studies employed such an approach. This points to opportunities for future research. Combining supervised training (in groups) with unsupervised or remotely supervised individual exergame-based training at home might be an elegant way to provide a socially supportive and motivating environment while also providing the conditions for more individualized and self-determined training. This approach would also allow for more frequent training that can easily be integrated into daily life by reducing the barriers to engaging in physical and cognitive training. This, in turn, would further enhance the trainings' ecological validity (Chang et al., 2022). To the best of our knowledge, this specific approach has not yet been investigated. However, there is evidence from one RCT (Manser and de Bruin, 2024) and two pilot studies (Allegue et al., 2022; Manser et al., 2023) in MOA showing that a combination of face-to-face and remotely monitored (Manser et al., 2023; Manser and de Bruin, 2024) or fully remotely monitored (Allegue et al., 2022) home-based exergame training can promote motivation of study participants (Allegue et al., 2022; Manser et al., 2023; Manser and de Bruin) and results in high adherence rates (Manser et al., 2023; Manser and de Bruin, 2024). The training concepts comprised various strategies to enhance self-efficacy (Manser et al., 2023; Manser and de Bruin, 2021), such as motivational interviewing (Allegue et al., 2022), or were specifically co-designed and developed to meet the needs and requirements of end users (Manser et al., 2023; Manser and de Bruin, 2021; Manser and de Bruin). These preliminary findings highlight that well-designed individualized exergame-based training concepts can lead to high adherence rates and internalization of training motivation, even when only partially or remotely monitored. However, the results of our meta-analysis suggest that adding in-person group training to the remotely supervised individual home-based training may further improve the effectiveness of such exergame-based training approaches on cognitive functioning in MOA.

As an alternative option to incorporate social elements into the home-based exergaming experience, technical options should be co-designed, developed and investigated. These could include virtual group sessions or multiplayer modes with collaborative challenges, scheduled online tournaments, online leaderboards with benchmarking of performance to compare one's performance with others, integration of voice and video calling features within the game for real-time communication, and/or community forums. This would allow for greater social inclusion in the training experience for individuals with limited mobility or who live too far away to regularly attend group sessions. To ensure training fidelity in home-based training, technical features should be developed and investigated to monitor training fidelity in addition to adherence. These could, for example, monitor the movement quality and strategies used to maintain postural stability (Tahmosybayat et al., 2018), and individualize the training content to address specific deficits on that basis. Consequently, ample opportunities exist for future research to explore and develop innovative approaches that combine supervised group training with unsupervised or remotely supervised exergame-based training at home.

4.1.5. Other exergame-based training components

Our results suggest that the remaining training components of the reviewed exergame-based training interventions did not significantly moderate the training effectiveness on cognitive functioning in MOA. Thus, we cannot provide empirical support for the recommendations provided by Torre and Temprado (2022) (Torre and Temprado, 2022a) concerning the training frequency (i.e., 2–3 sessions per week), exercise duration (i.e., 45–60 min), personalization of training (i.e., monitoring and individualizing exercise difficulty and complexity), and specificity of training (i.e., analyzing the cognitive contents of games). Even though the findings of our quantitative analysis do not specifically support these recommendations, it should, however, be considered that the absence of a moderating effect of these training components can be related to several factors. First, the majority of studies applied the same characteristics (e.g., 65 % of studies applied a training frequency of 3 x/week) and only one study applied a training frequency of $\geq$ 4x/week (Zheng et al., 2022), although there is evidence that training frequency constitutes a significant moderator favoring higher training frequencies in conventional training ($\geq$ 3x/week (Chen et al., 2020) or $\geq$ 5x/week (Northey et al., 2018)) (Manser and de Bruin, 2021). Such a lack of heterogeneity concerning some exercise and training variables limited our analysis and may explain some of our inclusive results, particularly with respect to training frequency. These findings suggest that future research should investigate the influence of higher training frequencies of exergame-based training interventions on cognitive performance in MOA. In line with our previous recommendations, higher training frequencies could be easily implemented by combining fully supervised face-to-face training sessions in groups with individual home-based training and remote supervision. Second, our analysis did not find reliable evidence for optimal exercise durations of exergame-based training interventions to improve cognitive performance in MOA. The latter is perhaps related to the inclusion of cognitively impaired populations in the present meta-analysis. Based on the literature, for individuals with cognitive impairment, a higher training frequency with shorter sessions (15–30 min) may be preferable to achieve a similar training volume ($\sim$ 150 min/week) and prevent attentional exhaustion compared to healthy MOA (Manser, Adcock-Omlin, et al., 2023; Manser and de Bruin, 2021). Therefore, further research is needed to identify the most effective exergame-based training components for specific populations. Third, we were unable to analyze varying levels of cognitive demands because neither one of the reviewed studies reported this information nor any of the authors were able to provide this information upon request. These findings align with the observations of Torre and Temprado's (2022) review, which also noted a lack of systematic reporting and control of physical and cognitive demands in most studies (Torre and Temprado, 2022a) which calls for future efforts to improve the monitoring and reporting of such an important exercise variable (for a narrativ review on the relevance of this exercise variable, refer to (Herold et al. 2024)).

According to a previous study, exergaming leads to greater cognitive benefits when posing a higher degree of cognitive challenge to the trainee (Anderson-Hanley et al., 2015). However, the current limitations in the design of exergaming scenarios often do not allow to reach high enough levels of motor skills complexity and cognitive load (Temprado and Torre, 2022). For conventional training, it has been reported that moderately to highly challenging balance training leads to greater cognitive improvements (Sherrington et al., 2017). This emphasizes the importance of monitoring and individualizing the training load. Therefore, we advocate, among others (Herold, Gronwald, et al., 2020; Herold et al., 2019; Herold, Törpel, et al., 2020; Perrey, 2022) that future research efforts should put a strong emphasis on finding valid and

reliable parameters to monitor training load for physical training in general and exergame-based training interventions in particular (i.e., motor and cognitive complexity as well as exercise intensity) in order to improve the effectiveness of the intervention. Ideally, physical training including exergame-based training should be tailored to the individual capacities using specific physiological markers of the 'internal training load' (Herold et al., 2019; Impellizzeri et al., 2019). In this regard, we recommend for the practical implementation of exergame-based training to prescribe and monitor the exercise intensity preferentially based on markers of internal load (e.g., physiological markers such as % heart rate reserve), following the guidelines for exercise intensity classification provided by the American College of Sports Medicine (Garber et al., 2011) and to report both markers of external load and internal load to improve the comparability of exercise intensity across different studies (Gronwald et al., 2019; Herold, Törpel, et al., 2020). To monitor motoric and cognitive exergaming demands, validated game metrics or subjective self-report measures can be used because the latter generally have acceptable levels of validity (Ayres et al., 2021). However, relying on a single measure to capture the training load during or after completing a training session or task may be insufficient because neurocognitive task demands can change over time (Paas et al., 2003; Skulmowski, 2022). This highlights the importance of identifying specific physiological markers (e.g., brain activity patterns (Herold, Gronwald, et al., 2020) or markers of cardiac autonomic activity (Manser et al., 2021)) or game metrics that can provide a valid, reliable, and responsive measure of motoric and cognitive training demands.

4.2. Strengths and limitations

This systematic review and meta-analysis had several major strengths. First, we collaborated with a professional librarian to develop our search strategy. The librarian then translated the strategy into precise search strings for each database and conducted the ordered literature search. This approach maximized the likelihood of identifying all relevant articles for this systematic review. Second, we considered and analyzed the influence of a comprehensive set of exergame-based training components and moved beyond the limitations of previous literature reviews in this field (Manser and de Bruin, 2021; Torre and Temprado, 2022a), namely insufficient reporting of information on exergame-based training components in the reviewed studies, by attempting to contact the corresponding and/or last author of the study up to three times. This was done to obtain all relevant information and/or the raw data from the studies to ensure a complete analysis of the available evidence on the influence of training components on the effectiveness of exergame-based training interventions on cognitive functioning in MOA. Finally, we analyzed the domain-specific influence of each of these training components separately to identify potential differences between specific neurocognitive domains.

The following limitations of this work are important to consider when interpreting our findings. First and most importantly, our results from the moderator analyses were observational, as we compared between-study differences in training components. Conclusions regarding differences in effects due to variations in the training components would have been more robust if participants were randomly allocated to intervention groups differing in the respective exercise or training variable, and between-group comparisons were conducted within RCTs (Deeks et al., 2019). Due to the unavailability of such RCTs (Torre and Temprado, 2022a), we used this approach to gain an initial quantitative overview to guide future research on dose-response relationships in exergame-based training studies on cognitive functioning in MOA. Second, although we considered a comprehensive set of exergame-based training components allowing us to conduct a thorough analysis, it also made our analyses susceptible to false-positive results without the adjustment of the significance level to account for multiple comparisons (Deeks et al., 2019). Third, we included a diverse sample of populations. Although our planned subgroup analyses revealed no differences in the effectiveness of exergame-based training concerning the population type or cognitive status, based on the literature (Manser and de Bruin, 2021) different dose-response relationships may exist in different populations. Therefore, further research is needed to identify the most effective exergame-based training components to improve cognitive functioning in specific populations of MOA. Fourth, despite our best efforts to obtain the necessary data from all included studies, 21 author teams did not respond to our data requests by our communicated deadline, resulting in missing data for some variables in 68 % of the analyzed publications. Fifth, our focus on English publications might have excluded valuable research from non-English speaking research groups. Finally, we included only studies with inactive control groups. This decision was made to ensure that the between-studies variance was mainly based on the intervention components and not influenced by the choice of comparator. We deemed this approach was warranted since a recent systematic review showed exergames to be more effective on global cognitive functioning than conventional physical training (Soares et al., 2021). While this approach limited the number of included studies and reduced the generalizability of our findings, it enhanced the statistical power of our analysis.

4.3. Implications for research

Future research should use our findings as a supplement to the recommendations provided by Torre and Temprado's (2022) (Torre and Temprado, 2022a) for HOA and our earlier recommendations specifically for older adults with mild neurocognitive disorder (Manser and de Bruin, 2021) which build a promising basis to further optimize and develop exergame-based training concepts aiming to improve cognitive functioning in MOA. In prompting future directions of research and practical application, we strongly recommend - based on the evidence provided by previous qualitative reviews (Manser and de Bruin, 2021; Torre and Temprado, 2022a) and our meta-analysis - that future research should focus on exergame-based training approaches that (i) are conducted in a standing position focusing on step-based and whole-body movements, (ii) incorporate the cognitive task into the motor task, (iii) apply a moderate physical exercise intensity, (iv) is fully supervised, and (v) adopts mixed approaches of fully supervised face-to-face training sessions in groups with individual home-based training with remote supervision. In addition, future research should also seek to elucidate the influence of higher training frequencies and different training densities, and put a stronger emphasis on identifying valid and reliable parameters to monitor internal training load. Technical options to incorporate social elements into the serious gaming experience and to monitor training fidelity in addition to adherence should also be developed and investigated. Further neuroscientific research is necessary to identify the most effective exergame-based training components for specific populations and unravel their biological mechanisms of action on different levels of analysis (e.g., changes on molecular and cellular levels, functional and structural brain changes) (Herold et al., 2019). In this regard, RCTs should aim to systematically compare different exergame-based training components to provide more robust evidence on the optimal design of such interventions to improve cognitive functioning in MOA. Finally, and most importantly, it is imperative that all future research on (exergame-based) training strictly adheres to well-known guidelines and checklists to ensure an appropriate and complete reporting of important characteristics of (exergame-based) motor-cognitive training which would facilitate the comparability and reproducibility of the findings as well as the implementation in practical settings. Thereto, we recommend the latest version of the *"Consolidated Standards of Reporting Trials (CONSORT) Statement for Randomized Trials of Nonpharmacologic Treatments"* (Boutron et al., 2017) in line with the Consensus on Exercise Reporting Template (CERT) guideline (Slade et al., 2016) for reporting the study interventions.

4.4. Implications for clinical practice and policy

The dramatic increase in the global prevalence of disorders that negatively influence cognitive functioning (e.g., neurocognitive disorders such as Alzheimer's disease, Parkinson's disease, major depressive disorder or stroke) represents a key challenge for aging societies, leading to a significant rise in its societal impact and costs (Nichols et al., 2022; Wimo et al., 2023). To counteract the rising burden of such disorders, it is essential to take sustainable and effective countermeasures (World Health Organization, 2021). Notably, fostering the engagement in physical exercise and physical training was recently recommended for the prevention of neurocognitive disorders by a collaborative international guideline (Veronese et al., 2023). Promoting exergames provides a new and promising avenue for engaging MOA in physical exercise (Dove and Astell, 2017) because this type of simultaneous motor-cognitive training is the most effective for enhancing cognitive functioning in MOA with and without neurocognitive disorders (Blomstrand et al., 2023; Gavelin et al., 2021). Although it is well known that exergaming provides a multitude of additional advantages compared to conventional motor-cognitive training (see Introduction) (Aminov et al., 2018; Chen et al., 2023; Chu et al., 2022; Gallou-Guyot, Mandigout, Bherer, et al., 2020; Gallou-Guyot et al., 2022; Manser, Poikonen, et al., 2023; Mura et al., 2018; Nawaz et al., 2016; Panza et al., 2018; Ryan and Deci, 2000; Swinnen et al., 2022; Valenzuela et al., 2018; Zhao et al., 2020), previous research has been limited by the frequent use of commercially available products (Temprado, 2021) and thus have not yet been able to unlock the full potential of exergame-based training to improve cognitive functioning in MOA (Gallou-Guyot, Mandigout, Bherer, et al., 2020; Stojan and Voelcker-Rehage, 2019; Temprado, 2021; Valenzuela et al., 2018). Despite these limitations, our results provide evidence that exergame-based training is safe, has high attendance adherence, and can improve global cognition, complex attention, and executive functions, which is consistent with previous research in healthy MOA (Gallou-Guyot, Mandigout, Bherer, et al., 2020; Jiang et al., 2022; Torre and Temprado, 2022a) as well as MOA with a range of clinical conditions (Aminov et al., 2018; Cai et al., 2023; Chen et al., 2023; Li et al., 2022; Swinnen et al., 2022; Zhao et al., 2020). Based on these findings, it is recommended that policymakers and clinicians pave the way for the broad and sustainable implementation of exergame-based training in the prevention of neurocognitive disorders.

Moreover, our results suggest that in MOA the effectiveness of exergame-based training on cognitive functioning is moderated by specific training components, and that moderate and clinically relevant effects can be achieved with the appropriate choice of training components. To unlock the full potential of exergame-based training, funders are encouraged to support innovative and high-quality research projects that focus on maximizing the ecological validity of exergame-based training concepts and their transferability to clinical practice by integrating findings and recommendations of others (Torre and Temprado, 2022a) with our previous recommendations (Manser and de Bruin, 2021) and the present meta-analysis in the design of upcoming empirical studies.

5. Conclusion

Our meta-analysis revealed that in MOA exergame-based training was effective in improving global cognition, complex attention, and executive functions, but not learning and memory or visuospatial skills. The effectiveness of exergame-based training was moderated by several training components that have in common that they enhance the ecological validity of the training. Specifically, (i) step-based exergame training that (ii) can be classified as simultaneous-incorporated motor-cognitive training, (iii) is conducted at a moderate exercise intensity, (iiv) is fully supervised and (v) adopts mixed approaches of face-to-face training sessions in groups with individual home-based training with remote supervision that may involve relatives or caregivers to provide additional support should be employed. Therefore, it seems paramount that future research focuses on developing innovative novel exergame-based training concepts that incorporate these (and other) components to enhance their ecological validity and transferability to clinical practice. This should be achieved by iteratively co-designing, developing, testing, and refining innovative exergame-based training concepts for specific target populations by integrating our findings with previous recommendations on the design of exergame-based training.

Moreover, several areas of interest for future research were identified. To enhance exergame-based training approaches, it is recommended to (i) explore higher training frequencies and different training densities, (ii) identify valid and reliable parameters to monitor internal training load, (iii) explore technical options for incorporating social elements into the serious gaming experience to create a more interactive and communal experience, (iv) to identify the most effective training components for exergame-based training for specific populations to improve their cognitive performance, and (v) to unravel the biological mechanisms of action driving potential effects of exergame-based training on measures of cognitive functioning. In this context, we strongly advocate that future research on (exergame-based) training strictly adhere to well-known guidelines and checklists to improve the rigor and completeness of reporting fostering reproducibility when developing, investigating, or implementing exergame-based training concepts in different settings.

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CRediT authorship contribution statement

The study was conceptualized by Patrick Manser, and the study protocol was collaboratively developed by all authors. Patrick Manser was responsible for the literature research. The screening and selection process as well as the risk of bias assessment of individual studies was done by Patrick Manser and Fabian Herold, with Eling D. de Bruin acting as a referee in case of disagreements between the two independent reviewers. Patrick Manser was responsible for the data collection process, data synthesis, and analysis of risk of bias and heterogeneity across studies, which was supervised by Eling D. de Bruin. All the data retrieved in these tasks were cross-checked by Fabian Herold. Patrick Manser was responsible for writing the manuscript. Fabian Herold and Eling D. de Bruin contributed to the revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

Declaration of Competing Interest

None.

Data Availability

All data analyzed in this study is included in the article and supplementary files. Further inquiries can be directed to the corresponding author.

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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.arr.2024.102385.

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