

The influence of open-skill and closed-skill sports on executive functions: a systematic review

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Abstract

Aims/Background Open-skill sports are reportedly more effective than closed-skill sports in improving executive functions. However, it remains unclear as to its superiority in specific components of executive functions and specific populations. This review aims to explore the degree to which specific components of executive functions are affected by different sport types, open-skill sports and closed-skill sports, among different age groups.

Methods Relevant articles published from 1st January 2000 to 31st December 2023 were searched and obtained from four databases, namely EBSCO, PubMed, Web of Science, and Science Direct. These studies were selected through a carefully established article-filtering workflow, governed by a set of inclusion and exclusion criteria, and the quality assessment was carried out independently by each researcher.

Results Out of the 30 studies included for this systematic review, eight studies demonstrated the beneficial impacts of open-skill sports on adults by improving three executive functions subcomponents, as compared with closed-skill sports. Six studies found that open-skill sports are conducive to inhibitory control and cognitive flexibility among children and adolescents, while four studies showed that open-skill sports greatly enhance inhibitory control in elderly individuals.

Conclusion Compared with closed-skill sports, open-skill sports have a favourable impact on inhibitory control and cognitive flexibility in children, adolescents, and adults, marked by shorter response time in inhibitory control tasks, as well as shorter response time and lower switch costs in cognitive flexibility tasks. In addition, relative to closed-skill sports, open-skill sports heightens accuracy in working memory tasks among adults.

Key words: Closed-skill sports; Event-related potential; Executive function; Open-skill sports; Review

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Introduction

Executive functions (EF), including inhibitory control, working memory and cognitive flexibility, represent a vital component of cognitive function and contribute to complex mental processing (Diamond, 2013). A plethora of evidence has underlined the significance of EF across all age groups, including the academic achievements of children and adolescents (Schmidt et al, 2017; Deer et al, 2020; Ameis et al, 2022), the work efficiency among adults (Cristofori et al, 2019; Marquez-Ramos et al, 2023), and the strong association with physical and mental health in the elderly (Dawson et al, 2015; McAlister and Schmitter-Edgecombe, 2016). Given the increasing emphasis placed on EF, a growing body of studies has reoriented their efforts in seeking effective ways to improve EF, e.g., exercise plans and physical exercises that are adopted in clinical settings.

The impact of physical activity on EF remains a contentious topic. Previous studies have suggested a clear benefit of unspecified physical activity in EF, with some papers advocating for implementation of physical activity programmes in schools to enhance EF so as to improve academic achievement (Deer et al, 2020; Ameis et al, 2022). While some studies report the suggestive evidence of improvement, others that follow more stringent criteria reveal a weaker association between physical activity interventions and enhanced EF. Notably, according to Diamond and Ling (2019), exercise interventions were among the least effective methods for improving EF. These findings do not necessarily negate the potential benefits of physical activity for overall cognitive health but they do suggest

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a potentially weaker link than previously thought. Thus, further high-quality research is warranted to identify the specific types of physical activities and intervention designs that may be the most effective in boosting EF, particularly in different age groups.

As discovered previously, several factors, especially the type of exercise, may modulate EF (Kramer and Erickson, 2007; Etnier and Chang, 2009; Khan and Hillman, 2014). For example, some sports, such as football, volleyball, and badminton, can significantly improve EF (Scharfen and Memmert, 2019; Alves et al, 2013), while others, including swimming, hiking, and gymnastics, can only improve physical fitness rather than cognitive function (Wang et al, 2013a; Tsai et al, 2017). Such exercise-specific effects on cognition can be explained by the distinctive cognitive demands of different sports types (Voss et al, 2010; Pesce, 2012). According to different cognitive demands, sports can be divided into two categories, namely open-skill sports (OSS) characterised by team confrontation, complex rules, and unpredictable movement, and closed-skill sports (CSS) that involve well-prepared activities in a relatively stable and predictable environment (Singer, 2000; Jacobson and Matthaeus, 2014). Thus, all sports activities can be rated in terms of cognitive demands on a spectrum ranging from the highly predictable CSS to the dynamic and unpredictable OSS. Likewise, some related studies adopted similar classification methods, dividing sports into either two categories (self-paced and externally-paced) (Ballester et al, 2019), or three categories (static sports, strategic sports, and interceptive sports) (Krenn et al, 2018; Rahimi et al, 2022). Previous interventional and observational studies revealed that OSS stands as a more effective option than CSS for improving EF (Hung et al, 2018; Koch and Krenn, 2021). This finding is supported by a meta-analysis focusing on children and adolescents with attention deficit hyperactivity disorder (Zhu et al, 2023). The benefits of OSS in EF enhancements are theoretically grounded in the skill transfer hypothesis (Taatgen, 2013), which explains the underlying mechanisms of sports training in cognitive improvement, i.e., cognitive skills trained through sports exercises, are transferable to untrained cognitive tasks, enabling participants taking OSS to acquire higher level of cognitive engagement to perform better in EF tasks (Krenn et al, 2018). Nonetheless, some studies have concerns regarding the favourable results based on this hypothesis, claiming that uncontrolled confounding factors, insufficient sample size, and deficient measurement could exaggerate the positive effect of OSS on EF (Fransen, 2022, Preprint; Furley et al, 2023). Several previous studies also suggest that the benefits of OSS for specific EF components, such as working memory and cognitive flexibility (Crova et al, 2013; Schmidt et al, 2015; Koch and Krenn, 2021), may vary significantly across different age groups (Gu et al, 2019), indicating age as an important mediating factor for the sports effect on EF.

Therefore, to better understand the relationship between sports types and EF improvement under the impact of age, this review focused on the influence of sports type on EF subcomponents (including inhibitory control, working memory, and cognitive flexibility) across different age groups (children and adolescents, adults, and elderly). To this end, behavioural and electrophysiological evidence was collected from relevant studies and analysed. The main purpose of this review is to provide a summative perspective for sports scientists and physical therapists to advance their research in the field of kinesitherapy.

Methods

Sources of data

The literature search of this systematic review was conducted following the PRISMA guidelines (please see **Supplementary material** for details) (Page et al, 2021). Studies published between 1st January 2000 and 31st December 2023 were searched and obtained from EBSCO (<https://www.ebsco.com/>), PubMed (<https://pubmed.ncbi.nlm.nih.gov/>), Web of Science (<https://www.webofscience.com/wos/>), and Science Direct (<https://www.sciencedirect.com/>), with no restriction on date, gender or age. The following three groups of retrieval terms were combined with the 'AND' and 'OR' operators for retrieval: 'open-skill', 'closed-skill', 'self-paced', 'externally paced', 'sports type', 'executive function', 'inhibition', 'inhibitory control', 'working memory', 'cognitive flexibility', 'sport' and 'exercise'. The retrieved articles were further screened against the inclusion and exclusion

criteria set forth in the following. The visualisation was conducted using RAWgraphs (<https://app.rawgraphs.io/>) (Mauri et al, 2017).

Inclusion criteria

Studies meeting the following criteria were included. First of all, titles and abstracts were screened by four authors to determine their relevance to the review topic. Thereafter, full texts were read to determine whether the studies met the inclusion criteria. In addition, the reference lists in the selected studies were also examined to determine studies highly related to the review topic. Finally, English-written papers describing interventional and observational studies conducted on human subjects, that examined the effect of sports on EF and compared OSS and CSS, were included in this systematic review. The age and exercise experience of subjects, study methods, and results must be clearly stated in the included articles. Additionally, EF tasks measuring at least one component of EF (inhibition, working memory, and cognitive flexibility) must be utilised.

Exclusion criteria

Duplicate studies were eliminated. Besides, studies satisfying the following criteria were also excluded. The titles, abstracts, and keywords of the included articles were screened, and then the full-texts of relevant articles were perused by the authors. Eventually, studies that adopted interventions other than sports, for example, video games, were excluded. Meanwhile, articles that did not use a standard task to assess EF were also excluded. Any disagreement between the authors of this review paper was solved through discussion until a consensus was reached.

Quality assessment of the included studies

The NIH Quality Assessment of Controlled Intervention Studies was used for assessing the quality of interventional studies, and the NIH Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (version 2021; <https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools>, accessed on 2 January 2024, NIH, Bethesda, MD, US) was adopted for assessing the quality of observational studies. Each tool is a 14-item checklist (Tables 1,2) (NIH Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies; NIH Quality Assessment of Controlled Intervention Studies). There are two responses to each item, coded as 'present' (1) or 'absent/unclear' (0). Finally, a total score was calculated. According to the study of Engeroff et al (2018), studies of a total score ≥ 12 points are regarded as high quality, 8–11 points as moderate quality, and < 8 points as low quality. The assessment was conducted by the authors separately. Discrepancies in points allocated were discussed among the authors of this review paper until a consensus was attained.

Results

The flowchart for article screening is displayed in Figure 1 (created using Photoshop, version 20.0.4, Adobe Systems, San Jose, CA, USA). After searching the four electronic databases, 2838 potential studies were obtained. Among them, 484 studies were retained after removing duplicates and irrelevant articles in EndNote (version X9, Clarivate Analytics, East Haven, CT, USA). A subsequent step in screening titles and abstracts further identified 77 studies based on relevance. At last, 47 studies were excluded in line with the exclusion criteria, leaving behind 30 articles as the primary sources for this systematic review. Additional studies were also adopted as supplementary materials for definitions and opinions.

The results showed that OSS were superior to CSS in improving EF in terms of three subcomponents, namely inhibitory control, working memory, and cognitive flexibility. (1) Specifically, OSS significantly improved inhibitory control in children, adolescents, and adults. (2) Compared with other age groups, the adult group benefited more from OSS in terms of working memory, as reflected in the higher accuracy. However, there was no significant difference in working memory performance between the two sports types in children and adolescents, and there was only a limited advantage for OSS in older adults. (3) Regarding cognitive flexibility, the superiority of OSS was evident in every age group,

Table 1. Assessment of observational studies

1. Was the research question or objective in this paper clearly stated?
2. Was the study population clearly specified and defined?
3. Was the participation rate of eligible persons at least 50%?
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?
5. Was a sample size justification, power description, or variance and effect estimates provided?
6. For the analyses in this paper, were the exposure(s) of interest measured before the outcome(s) being measured?
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?
10. Was the exposure(s) assessed more than once over time?
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?
12. Were the outcome assessors blinded to the exposure status of participants?
13. Was loss to follow-up after baseline 20% or less?
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?

Table 2. Assessment of interventional studies

1. Was the study described as a randomised trial, a randomised clinical trial, or an RCT?
2. Was the method of randomisation adequate (i.e., use of randomly generated assignment)?
3. Was the treatment allocation concealed (so that assignments could not be predicted)?
4. Were study participants and providers blinded to treatment group assignment?
5. Were the people assessing the outcomes blinded to the participants' group assignments?
6. Were the groups similar at baseline on important characteristics that could affect outcomes (e.g., demographics, risk factors, comorbid conditions)?
7. Was the overall drop-out rate from the study at endpoint 20% or lower of the number allocated to treatment?
8. Was the differential drop-out rate (between treatment groups) at endpoint 15 percentage points or lower?
9. Was there high adherence to the intervention protocols for each treatment group?
10. Were other interventions avoided or similar in the groups (e.g., similar background treatments)?
11. Were outcomes assessed using valid and reliable measures, implemented consistently across all study participants?
12. Did the authors report that the sample size was sufficiently large to be able to detect a difference in the main outcome between groups with at least 80% power?
13. Were outcomes reported or subgroups analysed prespecified (i.e., identified before analyses were conducted)?
14. Were all randomised participants analysed in the group to which they were originally assigned, i.e., did they use an intention-to-treat analysis?

as demonstrated by the shorter response time, higher accuracy, and lower switch costs. Such findings concerning the positive effects of OSS on overall EF extend the results of previous research, providing a unique perspective on the exercise-cognition relationship.

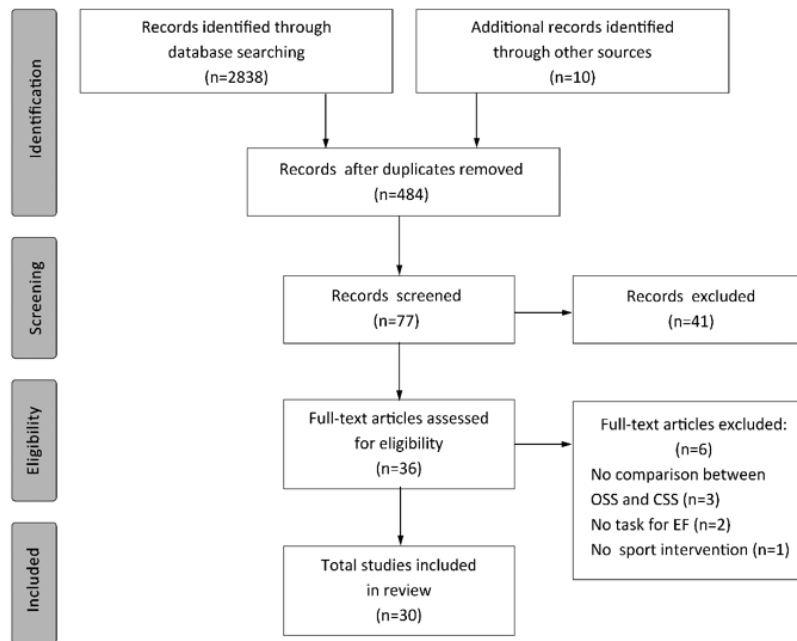


Figure 1. Flowchart for the article selection. OSS: open-skill sports; CSS: closed-skill sports.

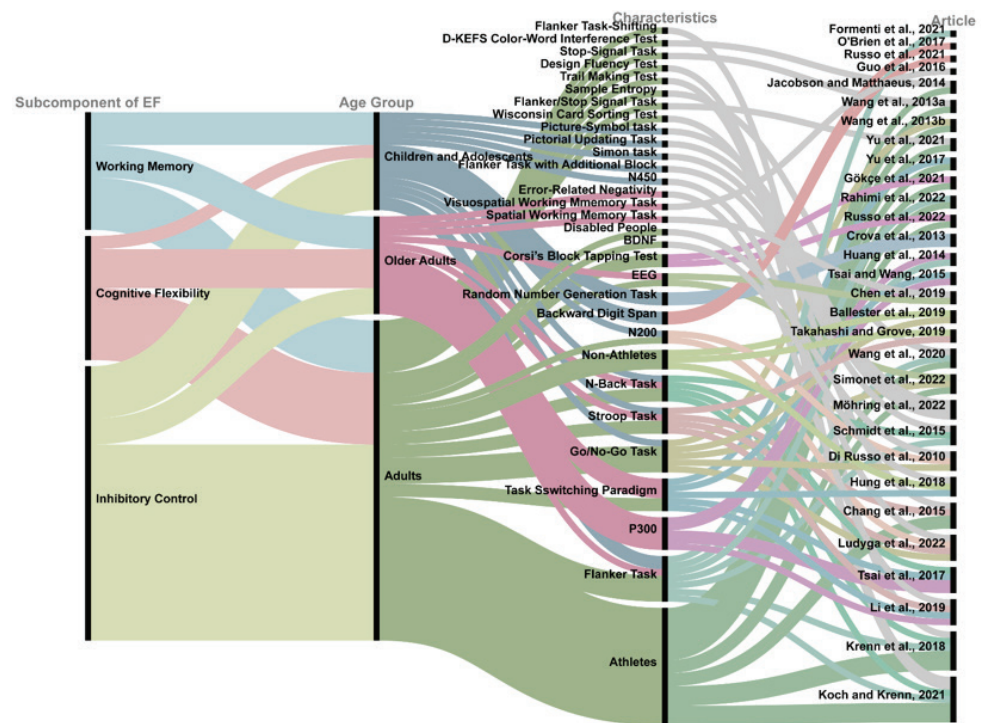


Figure 2. Correlations between EF subcomponents, age groups, and characteristics of the included studies. EEG: electroencephalograph; BDNF: brain-derived neurotrophic factor.

Study characteristics

The 30 included articles were published between January 2010 and March 2024. A comprehensive overview of the included studies is visualised in Figure 2. (Formenti et al, 2021; O’Brien et al, 2017; Russo et al, 2021; Guo et al, 2016; Jacobson and Matthaeus, 2014; Wang et al, 2013a; Wang et al, 2013b; Yu et al, 2021; Yu et al, 2017; Gökçe et al, 2021; Rahimi et al, 2022; Russo et al, 2022; Crova et al, 2013; Huang et al, 2014; Tsai and Wang, 2015; Chen et al, 2019; Ballester et al, 2019; Takahashi and Grove, 2019; Wang et al, 2020; Simonet et al, 2022; Möhring et al, 2022; Schmidt et al, 2015; Di Russo et al, 2010; Hung et al, 2018; Chang et al, 2015; Ludyga et al, 2022; Tsai et al, 2017; Li et al,

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2019; Krenn et al, 2018; Koch and Krenn, 2021.) Out of the included articles, six were interventional studies, among which two involved adults (non-athletes), three studies children and adolescents, and one study older adults. Five studies demonstrated a significant advantage of OSS intervention in EF enhancement, with no clear evidence of its beneficial effect on working memory. The characteristics of the included interventional studies are summarised in **Table 3** (Crova et al, 2013; Schmidt et al, 2015; O'Brien et al, 2017; Tsai et al, 2017; Takahashi and Grove, 2019; Hung et al, 2018).

Twenty-four included articles were observational studies. Among them, 15 studies involved adults (including 13 athletes and 2 non-athletes), 4 studies children and adolescents, and 5 studies older adults. The majority of them showed a higher level of EF in OSS participants than in CSS participants, confirmed by electroencephalograph (EEG), event-related potentials (ERPs) and physiological data. The characteristics of the included observational studies are summarised in **Supplementary Table 1** (Krenn et al, 2018; Jacobson and Matthaeus, 2014; Wang et al, 2013a; Wang et al, 2013b; Yu et al, 2017; Koch and Krenn, 2021; Wang et al, 2020; Gökçe et al, 2021; Yu et al, 2021; Rahimi et al, 2022; Russo et al, 2022; Simonet et al, 2022; Chang et al, 2015; Ballester et al, 2019; Formenti et al, 2021; Möhring et al, 2022; Ludyga et al, 2022; Russo et al, 2021; Li et al, 2019; Huang et al, 2014; Guo et al, 2016; Tsai and Wang, 2015; Chen et al, 2019; Di Russo et al, 2010).

Study	Participants	Intervention	Measurement	Results
1 Crova et al, 2013	Children, 9–10 Y, n=70	OSS: specialist-led enhanced PE programme CSS: generalist-led curricular PE programme 21 weeks	IC: random number generation task WM: random number generation task	IC: O > C WM: non-significant
2 Schmidt et al, 2015	Children, 10–12 Y, n=181	OSS: team games CSS: aerobic exercise Control: simple exercise Two lessons (45 min each) per week, lasting 6 consecutive weeks	IC: Flanker task WM: nonspatial n-back task CF: additional block in Flanker task	IC: non-significant WM: non-significant CF: O > C
3 O'Brien et al, 2017	Children, 6–8 Y, n=51	OSS: various OSS CSS: various CSS Control: sedentary 30 min	WM: backward digit span	WM: non-significant
4 Tsai et al, 2017	Older adults, 60–80 Y, n=64	OSS: table tennis training CSS: bicycle ergometer or treadmill Control: balance and stretching programme Three sessions (40 min each) per week, lasting 24 weeks	WM: N-back Task CF: task switching paradigm	WM: C > O (AR) CF: O > C (RT, SC) P300: non-significant
5 Takahashi and Grove, 2019	Adults, MA=20.9 ± 0.2Y, n=20	OSS: badminton session CSS: running session Control: sedentary 10 min	IC: Stroop/reverse-Stroop test	IC: O > C
6 Hung et al, 2018	Adults, MA=23.15 ± 2.48Y, n=20	OSS: badminton session CSS: running session 30 min	CF: task switching paradigm	CF: O > C (SC) with higher serum BDNF levels

Note: OSS: open-skill sports; CSS: closed-skill sports; Y: years old; MA: mean age; PE: physical exercise; AR: accurate rate; SC: switch costs; IC: inhibitory control; WM: working memory; CF: cognitive flexibility; O > C: OSS shows a greater advantage than CSS; C > O: CSS shows a greater advantage than OSS; BDNF: brain-derived neurotrophic factor.

Table 4. Results of quality assessment for intervention studies

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Sum Scores
Takahashi and Grove, 2019	0	0	0	0	0	1	1	1	1	1	1	1	1	1	9
Hung et al, 2018	0	0	0	0	0	1	1	1	1	1	1	1	1	1	9
Crova et al, 2013	1	0	0	0	0	1	1	1	1	0	1	0	1	1	8
Schmidt et al, 2015	1	0	1	1	1	1	1	1	1	1	1	0	1	1	12
O'Brien et al, 2017	1	0	0	0	0	1	1	1	1	1	1	1	1	1	10
Tsai et al, 2017	1	1	1	1	1	1	1	1	1	1	1	0	1	1	13

Table 5. Results of quality assessment for observational studies

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Sum Scores
Krenn et al, 2018	1	1	1	1	0	1	0	0	1	0	1	0	1	0	8
Jacobson and Matthaeus, 2014	1	1	1	1	1	1	0	0	1	0	0	0	1	0	8
Wang et al, 2013a	1	1	1	1	0	1	0	0	1	0	1	0	1	1	9
Wang et al, 2013b	1	1	1	0	0	1	0	0	1	0	1	0	1	0	7
Yu et al, 2017	1	1	1	1	0	1	0	0	1	0	1	0	1	1	9
Koch and Krenn, 2021	1	1	1	0	1	1	0	0	1	0	1	0	1	0	8
Wang et al, 2020	1	1	1	0	0	1	0	0	1	0	1	0	1	0	7
Gökçe et al, 2021	1	1	1	0	1	1	0	0	1	0	1	0	1	0	8
Yu et al, 2021	1	1	1	0	1	1	0	0	1	0	1	0	1	1	9
Rahimi et al, 2022	1	1	1	0	1	1	0	0	1	0	1	0	1	0	8
Russo et al, 2022	1	1	1	0	1	1	0	0	1	0	1	0	1	1	9
Simonet et al, 2022	1	1	1	0	1	1	0	0	1	0	1	0	1	0	8
Chang et al, 2015	1	1	1	1	0	1	0	0	1	0	1	0	1	0	8
Formenti et al, 2021	1	1	1	1	1	1	0	0	1	0	1	0	1	0	9
Möhring et al, 2022	1	1	1	0	1	1	0	1	1	0	1	0	1	1	10
Ludyga et al, 2022	1	1	1	0	0	1	0	1	1	0	1	1	1	1	10
Russo et al, 2021	1	1	1	0	0	1	0	0	1	0	1	0	1	1	8
Li et al, 2019	1	1	1	0	0	1	0	0	1	0	1	0	1	0	7
Huang et al, 2014	1	1	1	1	1	1	0	1	1	0	1	0	1	0	10
Guo et al, 2016	1	1	1	0	0	1	0	1	1	0	1	0	1	0	8
Tsai and Wang, 2015	1	1	1	0	1	1	0	0	1	0	1	0	1	0	8
Chen et al, 2019	1	1	1	0	0	1	0	0	1	0	1	0	1	0	7
Ballester et al, 2019	1	1	1	0	1	1	0	0	1	0	1	0	1	1	9
Di Russo et al, 2010	1	1	1	0	0	1	0	0	1	0	1	0	1	0	7

Results of quality assessment

The results of quality assessment are displayed in [Tables 4,5](#) (Takahashi and Grove, 2019; Hung et al, 2018; Crova et al, 2013; Schmidt et al, 2015; O'Brien et al, 2017; Tsai et al, 2017;

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Krenn et al, 2018; Jacobson and Matthaeus, 2014; Wang et al, 2013a; Wang et al, 2013b; Yu et al, 2017; Koch and Krenn, 2021; Wang et al, 2020; Gökçe et al, 2021; Yu et al, 2021; Rahimi et al, 2022; Russo et al, 2022; Simonet et al, 2022; Chang et al, 2015; Formenti et al, 2021; Möhring et al, 2022; Ludyga et al, 2022; Russo et al, 2021; Li et al, 2019; Huang et al, 2014; Guo et al, 2016; Tsai and Wang, 2015; Chen et al, 2019; Ballester et al, 2019; Di Russo et al, 2010), showing an average score of 8.67. Among the six interventional studies, two were of high quality (Schmidt et al, 2015; Tsai et al, 2017), and four were of moderate quality (Crova et al, 2013; Hung et al, 2018; Takahashi and Grove, 2019; Jessica et al, 2021). Blinding was adopted in only two of these studies (Schmidt et al, 2015; Tsai et al, 2017), and randomisation was considered adequate in only one study (Tsai et al, 2017). Among the 24 observational studies, 19 were of moderate quality (Wang et al, 2013a; Huang et al, 2014; Jacobson and Matthaeus, 2014; Tsai and Wang, 2015; Guo et al, 2016; Chang et al, 2015; Yu et al, 2017; Krenn et al, 2018; Ballester et al, 2019; Formenti et al, 2021; Gökçe et al, 2021; Koch and Krenn, 2021; Russo et al, 2021; Yu et al, 2021; Ludyga et al, 2022; Möhring et al, 2022; Rahimi et al, 2022; Russo et al, 2022; Simonet et al, 2022), and five were of low quality (Di Russo et al, 2010; Wang et al, 2013b; Chen et al, 2019; Li et al, 2019; Wang et al, 2020). Blinding was adopted in only one study (Ludyga et al, 2022).

Discussion

The purpose of this systematic review is to dissect the relationship between different types of sports exercises and EF subcomponents across various age groups. The results revealed a comprehensive superiority of OSS in EF enhancement compared to CSS, with some specific impacts of OSS on different subcomponents across various age groups discussed in the following.

Effects on inhibitory control

Numerous studies have demonstrated that both CSS and OSS can improve inhibitory control, with the latter offering a more significant benefit, marked by a shorter reaction time on inhibitory tasks (Wang et al, 2013a; Krenn et al, 2018; Wang et al, 2020; Rahimi et al, 2022; Simonet et al, 2022). In some cases, OSS training may also lead to higher accuracy (Rahimi et al, 2022).

Comparison among age groups

The advantages of OSS for inhibitory control appear to be consistent across different age groups. Evidence has suggested that long-term exercise can more effectively improve inhibitory control than short-term exercise for children and adolescents. For instance, a 6-week exercise intervention study conducted by Schmidt et al (2015) on children did not significantly impact inhibitory control ability among the OSS, CSS and control groups; however, a study by Crova et al (2013) found that an extended exercise intervention (lasting 6 months) had a superior effect on inhibition. According to these findings, a greater improvement in EF was observed in the experimental group, implying that long-term OSS exercise has a more significant positive impact on inhibition. Additionally, results from observational studies also provide evidence consistent with this body of findings. For example, Formenti et al (2021) found that children regularly participating in OSS (more than 3 years) displayed greater accuracy and faster response time in the Flanker tasks, as compared with their peers practising other types of sports or no exercise, indicating a higher level of inhibition. Besides, Ludyga et al (2022) further corroborated these findings using the Stroop task and reported that the longer time spent in OSS was associated with better performance in inhibition tasks; such improvement was substantiated through EEG recordings conducted in the same study. To be specific, children and adolescents with a long history of OSS participation exhibited greater negativity in the N450 and N200 ERP components, suggesting stronger inhibitory abilities. Taken together, these research results suggest that long-term OSS is more conducive to improving inhibitory control in children and adolescents.

Interestingly, even short-term OSS interventions can significantly improve inhibitory control in young adults. Through examining non-athlete participants who underwent a 10-minute intervention of badminton (OSS), running (CSS), or sitting (control), Takahashi

and Grove (2019) reported that there was no pre-test difference in inhibition between the groups, and only the badminton group displayed a significant increase in inhibition after the intervention. Similarly, Hung et al (2018) demonstrated that college students who participated in a 30-minute badminton intervention showed improved inhibition compared with those who ran. Additionally, numerous studies have documented the long-term benefits of OSS for athletes. After undergoing regular training for periods ranging from 6 months to several years, athletes specialising in OSS consistently outperform those specialising in CSS during inhibitory tasks (Wang et al, 2013a; Krenn et al, 2018; Wang et al, 2020; Rahimi et al, 2022; Simonet et al, 2022). Some of the results are also supported by studies deploying EEG recordings. For example, utilising the multi-scale entropy analysis (MSE) of EEG to investigate the differences in Flanker task performance between OSS athletes and CSS athletes, Wang et al (2020) found that the OSS group manifested abilities to tackle cognitive control tasks of higher complexity at coarser time scales.

For older adults, the advantage of OSS over CSS in promoting inhibition is primarily substantiated by EEG data. In the studies performed by Li et al (2019) and Huang et al (2014), the Stroop task and Flanker task, respectively, were utilised to assess older adults engaged in regular exercise (CSS and OSS groups). Despite the absence of behavioural differences between the two groups, both studies revealed significant differences in EEG data. Compared with the CSS group, the OSS group showed a larger amplitude of the P300 component during these inhibitory tasks. Therefore, relative to CSS, OSS offers some cognitive benefits for inhibition in older adults, although it is less pronounced than in younger populations.

Of note, the advantages of OSS extend beyond healthy individuals. Studies have indicated that OSS can significantly benefit individuals with disabilities who experience cognitive deficits. A study conducted by Di Russo et al (2010) employed EEG recordings to compare disabled athletes of different sports with healthy non-athletes. This study found that wheelchair basketball players significantly outperformed disabled swimmers and were comparable to healthy non-athletes in accuracy in responding to inhibitory tasks. Such differences or similarities were also reflected in the EEG data. The N2 component of ERP in wheelchair basketball players was comparable to that in healthy non-athletes and was delayed and reduced in disabled swimmers. These observations illustrate that the inhibitory deficits present in disabled individuals can be effectively compensated for by OSS. Overall, the study performed by Di Russo et al (2010) highlighted that OSS offers not only physical benefits but also cognitive advantages compared with CSS. For individuals with disabilities, OSS might be a more suitable option for improving social adaptability and quality of life.

Factors responsible for inconsistent results

Despite the advantages of OSS described above, several studies reported no significant differences in inhibition between adult athletes participating in OSS and those in CSS (Wang et al, 2013b; Koch and Krenn, 2021; Yu et al, 2021; Ludyga et al, 2022). For example, Rahimi et al (2022) and Yu et al (2021) both utilised the Flanker task to compare the two sports types in college athletes. However, only the former discovered that OSS athletes outperformed CSS athletes in terms of response time and accuracy, while the latter did not suggest any significant difference. Impacts of CSS and OSS were also analysed among young athletes by Simonet et al (2022) and Wang et al (2013b) using the Go/No-Go task, but a significant advantage in the response time among the OSS athletes was observed only in the former study. Some authors believe that such inconsistent results may be ascribed to the defects in the existing measurement tools (Furley et al, 2023). The inhibitory control of a person can only be partly assessed in a single task, which unfortunately may lead to inconsistent results even if the participants to be assessed have same characteristics (Diamond, 2013; Koch and Krenn, 2021). In this regard, conducting multiple tasks in the same study may help reduce methodological bias to some extent. For example, in the study carried out by Ludyga et al (2022), both the Stroop task and Go/No-Go task were adopted. The advantage of OSS was significant for improving the response time of study participants in the Stroop task, but not in the Go/No-Go task, indicating a more beneficial role of OSS in inhibitory control than CSS. Therefore, future studies should advocate for the use of multiple measuring tasks to reduce the result discrepancies.

It has been suggested by some researchers that professional athletes, who are subjected to excessively intense exercise and training, may face impairment of cognition, including EF, as a result of oxidative stress and the accumulation of peroxides and free radicals (Chang et al, 2015). This notion may account for the resulting inconsistency among studies that reveal no difference in inhibition between OSS and CSS participants. However, there is a lack of experimental evidence to substantiate this phenomenon in humans, since only animal experiments have been conducted thus far. In a murine study by Rosa et al (2007), remarkable increase in brain oxidative stress along with notable cognitive impairment was observed in the exercise group relative to the control group. The association between excessive exercise and cognitive impairment reveals that high intensity of exercise may undercut the cognitive benefits induced by OSS, lending support to the observation that OSS advantages are minimal in adult athletes, as reported in certain studies. Therefore, it is recommended that moderate OSS should be advocated for adults to achieve the optimal effect on inhibitory control.

Effects on working memory

Existing evidence supports that OSS is more beneficial for improving working memory than CSS, as demonstrated by the higher accuracy of OSS participants (Tsai et al, 2017; Krenn et al, 2018; Gökçe et al, 2021; Koch and Krenn, 2021). Interestingly, CSS athletes participating in OSS were found to have improved 2-back task performance, suggesting that exposure to OSS, even at a low level, could benefit working memory (Koch and Krenn, 2021). The improved ability to recall and use information may be particularly advantageous for real-world problem-solving.

Comparison among age groups

As found in multiple studies investigating children and adolescents (6–18 years old), both CSS and OSS exercise interventions, regardless of the length (short-term or long-term), can improve working memory. For example, Jessica et al (2021) discovered that the working memory in children (6–8 years old) exposed to 30-minute interventions of OSS (basketball, soccer, etc.) and CSS (running, circuit training, etc.) was improved after the intervention compared with the control group (homework revision), but there was no significant difference between the exercise groups (OSS vs. CSS) in the backward digit span task. Similarly, interventional studies performed by Schmidt et al (2015) lasting 6 weeks and by Crova et al (2013) lasting 21 weeks demonstrated improvements in working memory among children and adolescents who participate in sports, regardless of their types, but no significant difference in this EF subcomponent was detected between the CSS and OSS groups. These findings were supported by several observational studies (Russo et al, 2021; Möhring et al, 2022).

Most of the available studies on adults focus on athletes, while research on non-athletes remains scarce, putting a limit on findings extrapolation to adult populations of different backgrounds. The generalizability of these study findings is further constrained by inconsistency among the existing results. Some studies showed that OSS athletes have significantly stronger working memory than CSS athletes. For example, Krenn et al (2018) found that athletes in the OSS group exhibited more correct reactions in the 2-back task than those in the CSS group. Likewise, higher accuracy was observed among OSS athletes in the studies by Koch and Krenn (2021) using the 2-back task, and by Gökçe et al (2021) using Corsi's Block Tapping test. Through correlation analyses, Koch and Krenn (2021) also reported that errors committed by individuals with greater involvement in OSS were fewer compared to those involved in CSS.

To date, few studies have focused on the influence of sports on the working memory of the elderly, and studies comparing OSS and CSS are also lacking. Nonetheless, according to existing studies, OSS has limited benefits on the working memory of the elderly. The study by Chen et al (2019) provided evidence supporting the advantages of OSS. Functional magnetic resonance imaging results in this study indicated greater brain activation in the prefrontal lobe, ACC/SMA, and hippocampus among OSS participants than in the other two groups, proving that OSS can beneficially improve the working memory domain of the brain. In the same study, the behavioural results stemming from a spatial working memory task demonstrated improved performances in both the OSS and CSS participants, with no significant difference detected between the two groups. Conversely, Tsai et al (2017)

found that CSS was more effective in improving the working memory of the elderly. After 6 months of exercise intervention (three times a week, 40 minutes each time), researchers discovered that only the CSS group exhibited significantly increased accuracy in both the 1-back and 2-back tasks after the exercise intervention. In comparison, the OSS group showed an increase in accuracy only in the 1-back task. Another exception is the study conducted by Guo et al (2016), in which the visuospatial working memory task results indicated that the elderly individuals who were regularly engaged in the exercise had higher working memory than those who were sedentary. However, there was no significant difference in working memory between participants in the OSS and CSS groups.

Factors responsible for inconsistent results

The advantages of OSS in working memory are not represented in every relevant study. For instance, Corsi's Block Tapping-Backwards task and the match-to-sample test adopted in studies by Russo et al (2022) and Chueh et al (2017), respectively, did not detect significant differences in the results between the two groups of athletes (OSS and CSS). In the study by Chueh et al (2017), there was no significant difference in the P300 component between athletes from OSS and CSS groups. In addition to the methodological influence and the cognitive impairment caused by excessive exercise, these results may also indicate a limited effect of OSS on the working memory in adults. In a meta-analysis by Heilmann et al (2022) regarding the impact of OSS and CSS on the three components of EF, OSS exhibited the smallest effect size on the working memory. This may explain the lack of significant difference in the working memory between OSS and CSS athletes in some studies.

Collectively, these results suggest that neither CSS nor OSS offers a clear advantage for working memory improvement in children, adolescents, and older adults. Despite the benefits demonstrated in adults, particularly those participating in OSS, the overall evidence in support of the advantages of CSS and OSS remains inconclusive.

Effects on cognitive flexibility

Based on this systematic review, we found that the positive effect of OSS on cognitive flexibility is highly consistent across all age groups. For children, adolescents, adults, and the elderly, OSS brings obvious cognitive benefits and facilitates faster responses in a task-switching paradigm with fewer switch costs.

Comparison among age groups

Through a picture-symbol task, Möhring et al (2022) found that children and adolescents participating in OSS exhibited notable advantages in cognitive flexibility, as evidenced by the shorter response time and fewer switch costs. Furthermore, this advantage became more significant with the increased participation in OSS. Schmidt et al (2015) discovered that children undergoing the OSS intervention showed shorter response time, lower switch costs, and higher accuracy in a Flanker task than those in the CSS and control groups. This improvement was similarly observed in both pre-test performance and pre-to-posttest changes in the task-switching paradigm. A systematic review by Shi et al (2022) also supported that OSS is more effective than CSS in improving cognitive flexibility in children and adolescents.

Likewise, with regard to adults, Krenn et al (2018) and Koch and Krenn (2021) indicated that OSS athletes exhibited higher cognitive flexibility than CSS athletes, as observed from the task-switching paradigm and Flanker task, respectively. The superiority of OSS over CSS in cognitive flexibility improvement also extends to the context of non-athletes. For example, from an interventional study, Hung et al (2018) provided evidence that after 30 min of running (CSS) or playing badminton (OSS), male students in the OSS group showed lower switch costs and higher serum BDNF levels than those in the CSS group. BDNF is a neurotrophic factor that contributes to the development and plasticity of neurons, and its increased serum concentrations have been proven to play an important role in exercise-induced cognitive improvement. Therefore, the elevated BDNF level in the OSS group is not merely an indicator but also a mediating factor contributing to cognitive flexibility improvement among those engaging in OSS.

Studies involving elderly individuals have discovered that those who are engaged in long-term OSS exhibit better cognitive flexibility than their peers, as supported by EEG

data. Tsai et al (2015; 2017) have conducted two studies on the elderly to examine the effects of different exercise types on EF. In one of the two studies, Tsai et al (2017) reported that elderly participants in the OSS group consumed significantly shorter response time and lower switch costs in a task-switching paradigm than those in the CSS group after a 24-week exercise intervention. In another study (Tsai and Wang, 2015), the elderly OSS participants were found to display a greater amplitude of the P300 component than their CSS counterparts, with a shorter response time in the task-switching paradigm, which was comparable to that reported in previous research (Hillman et al, 2006; Dai et al, 2013). Additionally, Li et al (2019) also reported that elderly individuals who regularly participated in OSS demonstrated a shorter ERN latency in a task switching paradigm. Besides, the EEG and physiological data, along with behavioural results, corroborated each other, demonstrating the advantage of OSS in improving cognitive flexibility.

Strengths and limitations

To the best of our knowledge, this review provides the first comparative analysis of the effects of OSS and CSS on three core components of EF, namely inhibitory control, working memory, and cognitive flexibility. The studies included in this review cover various age groups ranging from children, adolescents, adults to the elderly under controlled research conditions. Thus, the findings stemming from this systematic review offer novel insights that can assist in designing personalised exercise intervention programmes.

Nevertheless, certain limitations in this study should be noted. For instance, some factors such as gender and educational level, which may have confounding effect on the results, were not considered in our analysis, due to limited research attention and reporting on the impact of these factors. Furthermore, this systematic review also did not delve into exploring the impacts of OSS and CSS on subdomain components of EF, such as verbal working memory and visuospatial working memory under the umbrella of working memory. In addition, only studies published in the English language were included in this review, while relevant articles published in other languages were excluded.

Conclusion

In summation, OSS is more effective than CSS in improving EF. The findings of this review suggest that increased participation in OSS may heighten inhibitory control, working memory, and cognitive flexibility, corroborating OSS as a recommended method of physical therapy. However, an exclusive focus on healthy population in most existing research, which contribute to scanty findings on certain disease such as neurodegenerative diseases, underscores the need for further investigations that take brain mechanisms into account, in order to properly account for the inconsistencies seen in the results. In addition, more studies are warranted to explore the formulation of exercise plans tailored for both self-improvement and clinical applications.

Key points

- Executive functions are essential for the mental and physical health, personal development, and achievements of a person.
- Extensive research has indicated that OSS with high cognitive engagement is generally more effective on EF than CSS with low cognitive engagement.
- Our findings suggested that, compared with CSS, OSS has a favourable impact on inhibitory control and cognitive flexibility in children, adolescents, and adults, marked by shorter response time in inhibitory control tasks, and shorter response time and lower switch costs in cognitive flexibility tasks.
- Adults practicing OSS are able to react more accurately in working memory tasks than those practicing CSS.
- Meanwhile, OSS had a general superiority across the populations, irrespective of age, in improving cognitive flexibility.

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Availability of data and materials

All data, models, and code generated or used during the study appear in the article.

Author contributions

Conceptualisation, JHL; methodology, JHL; software, JHL; validation, JHL and ZJZ; formal analysis, JHL; investigation, JHL; resources, JHL; data curation, JHL, ZJZ, GXN and YLL; writing—original draft preparation, JHL; writing—review and editing, JHL, ZJZ, GXN and YLL; visualisation, JHL; supervision, GXN and YLL; project administration, JHL, GXN and YLL; funding acquisition, GXN and YLL. All authors contributed to important editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

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Conflict of interest

The authors report there are no competing interests to declare.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at <https://www.magonlinelibrary.com/doi/suppl/10.12968/hmed.2024.0168>.

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