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The Impact of Practicing Open- vs. Closed-Skill Sports on Executive Functions – An Updated Meta-Analytic Review with Focus on Characteristics of Sports

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Abstract

Exercise modes can be categorised based on the skills (open vs. closed skills) required, which implicates various demands on cognitive skills, especially executive functions (EFs). Thus, their practice may have varying effects on EFs. There is a lack of detailed analysis of cognitive affordances and a suitable classification of sports. It is hypothesized that the similarity of cognitive affordances leads to small effect sizes when comparing OSE and CSE. The current meta-analysis evaluates the variances in cognitive skills caused by particular sport modes. Four research databases (Web of Science, PubMed, ScienceDirect, PsychINFO) were searched for cross-sectional studies that compare the effect of OSE and CSE on EFs. A total of 19 studies were included, revealing an overall effect size of $g = 0.174$ ($p = .157$) for OSE versus CSE. The subgroup analysis revealed the effects for various EFs (CF: $g = .210 >$ IC: $g = .191 >$ WM: $g = .138$; $p > .05$), which could be characterised as low to moderate. The hypothesis that studies with the smallest effect sizes compare sport modes with similar cognitive demands was rejected. The paper discusses the differentiation of sports into OSE and CSE, and presents new approaches for their categorisation.

Keywords: Executive Functions, Cognitive Functions, sports experience, sport modes, cognitive skill transfer

1 Introduction

Executive functions (EFs), including cognitive skills such as working memory, inhibitory control, cognitive flexibility, planning, reasoning, and problem-solving, enable humans, especially athletes, to display goal-directed behaviours, adapt to novel situations, and manage social interactions (Cristofori et al., 2019). Results of researches in sport science reveal that the expression of EFs can benefit from physical activities (for reviews, see Etnier & Chang, 2009; Khan & Hillman, 2014) and the exercise of sport (Vestberg et al., 2012), or could be impacted by performing certain types of sports (Formenti et al., 2021). Numerous studies indicate that athletes have better EF performance than non-athletes (for review, see Scharfen & Memmert, 2019). Recent studies evaluated the differences in EF between athletes with high expertise in open- or closed-skill sports, and classified open-skill sports as superior, in terms of EF performance (Jacobson & Matthaeus, 2014).

A few studies extended the research question from a simple comparison between athletes' and non-athletes' expression of EFs, to implementing a tangible sports performance (soccer performance: Heilmann et al., 2021; ice hockey performance: Lundgren et al., 2016). The current meta-analytic review investigates the effect of practicing open- or closed-skill sports on the expression of EFs. Furthermore, the characteristics of closed- and open-skill sports are investigated, and subgroup and moderator analysis is done to determine if the effects are more or less critical for different kinds of EFs and if the age of samples affects the outcome.

1.1 Executive Functions and Sports Experience

Previous research reveals that practicing a sport could support the expression of EFs. The findings of studies relating to the sport of soccer (Huijgen et al., 2015; Verburgh et al., 2016), tennis (Mallek et al., 2017), basketball (Furley et al., 2013;

Furley & Memmert, 2010; Kioumourtzoglou et al., 1998), volleyball (Alves et al., 2013; Zhang et al., 2009) and others, support this hypothesis. The studies examined the difference between athletes' and non-athletes' performance of EFs, and reported that athletes show superior EFs than non-athletes. The hypothesis could be expanded because numerous studies indicated differences in EFs, based on the particular type of sport that they choose to study (open vs. closed skill).

1.2 Effects of Open- and Closed-Skill Sport Practice

Sports, especially movement science, differentiates sporting movements based on their special environmental and task requirements and the resulting degrees of variability of movement execution on a horizontal continuum within the extremities of closed and open skills.

Gymnastics, track and field, swimming, and shooting, could be characterised as closed-skill sports (Knapp, 1963; Singer, 2000; Tsai & Wang, 2015). In these sports, a particular skill, such as the Biellmann pirouette in figure-skating or the triple somersault in water jumping, is often the goal and purpose of the movement itself. In Category 1 of closed-skill sports, the form of movement is fairly fixed for the specific type of sport, and the environmental and task requirements are primarily constant during the execution of the movement (e.g., gymnastics). In Category 2, which comprises the continuum of closed to open skills, the environmental conditions are already known (e.g., athletics disciplines), and so could be implemented in the pre-existing program of movement.

Tennis, soccer, alpine skiing, and surfing could be defined as open-skill sports. These skills often serve to achieve a goal and purpose that are independent of their external form (e.g., skiing in the mogul slope). Open-skill sports are characterised by a wide range of variations and a low level of dependency on certain specific movement sequences (e.g., combat, team, and nature sports such as windsurfing, alpine skiing, etc.). In Category 3 of open-skill sports, athletes can foresee situational conditions to a limited extent only (e.g., in nature sports such as surfing and skiing). In Category 4, athletes cannot at all predict the diverse environment (e.g., combat and team sports), and so have to react very quickly and dynamically to constantly changing movement requirements.

The environmental conditions or affordances of movements could impact the cognitive skills of practitioners. For example, Furley and Memmert (2012) showed that expert basketball players can resist competing stimuli and focus on the task in a better manner than novices. With this skill, they can make better tactical decisions than amateurs. Closed-skill sports are performed in conditions that remain primarily constant, and are known or irrelevant for the course of movement. Thus, the athletes do not have to adapt to changing environmental conditions as often as in open-skill sports. For these reasons, CSEs are considered to have lower demands on cognitive skills.

The underlying theory in the current study is broad skill transfer hypothesis (Taatgen, 2013). This approach assumes that the cognitive skills achieved while training for or practicing a particular sport will also be transferred to untrained cognitive performance or tasks. Thus, in the example of OSE, a training to switch between different strategies in tennis (baseline vs. serve and volley) would lead to higher performances in CF in laboratory.

Many researches show positive correlations between practicing open-skill sports and EF performance (Jacobson & Matthaeus, 2014; Krenn et al., 2018; Wang et al., 2013). Researches that examined EFs in open-skill sports report that open-skill sports are superior to closed-skill sports in the context of development of EFs (e.g., Koch & Krenn, 2021).

According to Yongtawee et al. (2021) and Krenn et al. (2018), when classifying sports as interceptive (boxing), strategic (soccer), or static (gymnastics) based on the interaction between teammates and opponents and the dynamic environment, interceptive and strategic sports athletes tend to show better processing speed and cognitive skills (Yongtawee & Woo, 2017), when compared to those who engage in static sports. Another classification of sport modes suggested by Ballester et al. (2019) is externally-paced (e.g., baseball) and self-paced (e.g., swimming). The definition of these categories is similar to that of OSE and CSE.

Overall, the classifications of CSE and OSE are not exhaustive with respect to the impact on cognitive functions. For example, even the tripartite classification by Yongtawee et al. (2021) could not differentiate between static sports with high and low cognitive affordances (e.g., gymnastics vs. athletics).

There is an ongoing debate about the interaction between affordances of various sport types and EFs, and whether only OSE could support the development of EFs. Furthermore, there is a lack of knowledge concerning the relationship between performance in closed-skill sports and EFs, and possible mechanisms of promoting EFs.

Recent studies by Zhu et al. (2020) and Gu et al. (2019) investigated the effect of OSE versus CSE on various cognitive functions. They did not focus on the characteristics of sports. The comparison of open vs. closed skills was limited and not discussed in relation to the specific affordances of sport modes. The subgroup analysis focused only on the type of cognitive function or on the age of samples. The authors studied a broad range of cognitive functions: inhibitory control, cognitive flexibility, visuospatial attention, visuospatial working memory, processing speed, problem-solving, vigilance, and decision making (Zhu et al., 2020). Their studies did not clarify if CSE with high cognitive demands could lead to more or less the same improvements in EFs as OSE.

Therefore, the current systematic review and meta-analysis aim to evaluate the characteristics of sports evaluated in previous observational studies (using the continuum model described above), to identify the processes that can lead to an improvement in EFs. First, the differences between OSE and CSE's effects on EFs were retrieved from the latest research findings. For this purpose, a literature search was conducted in relevant databases. Then, the identified records were synthesized in a quantitative meta-analysis.

Based on the broad cognitive skill transfer hypothesis, we hypothesised that there could be reported differences between the EFs of open- and closed-sports athletes. The main difference that we considered was the focus on the examined sport modes in the included studies. Using this approach, we tried to find explanations for differences in the expression of EFs. We hypothesised that the effect sizes of group differences in studies on sport modes within categories 2 and 3 (e.g., athletics vs. canoe slalom) are smaller when compared to studies on sports within categories 1 and 4. This hypothesis suggests that the cognitive requirement of the sport should be considered when interpreting the effects of CSE vs. OSE. In addition, the sample's age and study quality should be regarded as a moderator while doing the meta-regression analysis.

2 Methods

2.1 Literature Search Strategy

The literature search was conducted using systematic review and meta-analysis, as recommended by the PRISMA statement for searching and reporting studies (Liberati et al., 2009). The search was done using a combination of the terms, a) "executive function" (MeSH Terms), b) "open-" or "closed-skill" or "exercise mode" and c) "sports" (MeSH Terms). The search terms are attached in Appendix A. Cross-sectional studies that reported relevant findings about the executive functions of OSE vs. CSE athletes were identified in the search. The research began with literature search at the beginning of October 2021 and ended with statistical analysis at the end of October 2021. Additionally, reference lists of included articles were created for further studies after confirming their eligibility.

Insert Figure 1 here

2.2 Selection Criteria

Full-text articles written in English language, published between 2000-01-01 and 2021-10-01, were considered as eligible for inclusion in the qualitative and quantitative analysis. Records were selected if they a) examined athletes of open- and closed-skill sports (min. of one sample group per category), b) stated a level of performance for the examined athletes, c) stated the age of the participants, d) measured at least one of the three core EFs (working memory, inhibitory control, cognitive flexibility), e) used a cross-sectional design for analysis, f) reported the differences of open- and closed-sports athletes using statistical analysis, and (g) presented the results in terms of mean, SD and sample size (by considering open and closed skills as independent variables). Studies that a) had medical questions, b) included disabled or impaired subjects in the study, or c) only used self-report or other psychometric measurements (questionnaires or ratings) for characterisation of EFs were excluded from the analysis.

2.3 Qualitative and Quantitative Analysis

The qualitative analysis included a comparison of studies based on outcome measure and test statistics, to identify the eligible studies. In addition, study designs and samples were compared and analysed in the context of the research question. Specifically, the exercise mode and type of sport were included in the discussion. The conducted tests were taken into consideration for the qualitative analysis of the systematic review.

The quantitative synthesis analysed studies that reported effect size, test statistics or result tables using means, SD or SE, and sample sizes for groups. Quantitative synthesis was made based on Hedge's *g* to correct for small sample sizes and Bessel correction for different sample sizes (*n*-1; Form. 1).

$$1) \qquad g = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{(n_1 - 1) \times s_1^2 + (n_2 - 1) \times s_2^2}{n_1 + n_2 - 2}}}$$

Subtasks in the studies with respect to different parameters were summarised based on overall effect size. Different categories of EFs (inhibitory control, working memory, and cognitive flexibility) were considered as subgroups in the meta-analysis. If the authors reported various measures for one subgroup, the combined effect for the EF was calculated. Overall effect sizes and effect sizes of single test studies were applied to Random Effect Model meta-analysis (k = 19). Omnibus test statistic Q was calculated to determine the variability in the distribution of effect size estimates, as done by Ellis (2010). Heterogeneity was indicated by I^2 and tested for the overall analysis. For every subgroup, the respective EF was calculated. Hedge's *g* was interpreted based on Cohen's guideline (Cohen, 2013), which suggests that 0.2 be considered as a small effect, 0.5 be considered as a moderate effect, and 0.8 be considered as a large effect. Thus, an I^2 of 25% was characterised as low, 50% as moderate, and values greater than 75% as highly heterogeneous (Higgins & Thompson, 2002). The significance of the *p*-value was set at $p < .05$.

Moderator analysis was conducted using a Mixed-Effect Model, by considering Tau^2 and Hedge's *g* as estimators of overall effect (age and study quality) and subgroup analysis (age). Study quality was not considered as a moderator of the subgroup analysis, as it has no relevance in terms of content. In addition, calendar age and study quality were established as continuous moderator variables (CI interval level: 95%).

Overall effect sizes (Hedge's *g*) and test statistics of meta-analysis were calculated in Rstudio (Version 1.4.1103, Rstudio PBC, Boston, Massachusetts, USA), using the "esc" package. Meta-regression was performed using the Jamovi software (Version 2.2.2), and package "meta".

2.5 Risk of Bias Assessment

Two independent reviewers (F.H. and H.W.) were designated to conduct the literature search, to avoid selection bias. They screened the titles, abstracts, and full texts of identified records, and rated the quality of studies using the NIH study quality assessment tool (NIH, 2021). In the event of discrepancies, a third reviewer was roped in to rate the particular study. Publication bias was studied using descriptive analysis of a funnel plot. Asymmetry or incompleteness of the funnel plot was interpreted as an indication of publication bias (Ellis, 2010).

3 Results

3.1 Study Selection

A flow diagram of the selection process is presented in Figure 1. The search was conducted on four electronic databases, namely Web of Science, PubMed, ScienceDirect, and PsychINFO. Studies of previous reviews (Gu et al., 2019; Zhu et al., 2020) on the differences in cognitive functions (EFs) achieved through exercise were included in the qualitative and quantitative analysis (first strategy). After the screening of articles on previous studies, 12 studies (out of 17) were identified as eligible. Four studies were excluded as the authors of the reviews had included intervention studies in their analysis. At the end of the search, 8812 potential articles were identified for the current study (second strategy). After the removal of duplicates, 5920 articles remained. After title and abstract screening, 41 titles remained for full-text search. 17 records were excluded because of the following reasons: (1) they had already been referenced in previous reviews (n = 12), (2) data was not available even after requesting the corresponding author (n = 3), (3) there was no EF-measure, (4) EF-measure was included only for higher EFs, (5) the EFs were categorised in an inappropriate form (n = 2), or (6) the identified record was an intervention or treatment study (n = 1). Three additional records were identified by cross-checking the references in the studies during full-text screening (third strategy).

After independent evaluation of full-texts based on the predefined inclusion criteria, seven new studies were included in the review (two reviewers agreed on the criteria). Thus, a total of 19 studies were selected for qualitative and quantitative analysis, systematic review and meta-analysis. These included articles are listed in Table 1. The quality of included articles was rated at 7.78 (Mdn: 8 [6-9]; SD: 0.69), with 100% agreement among all reviewers.

3.2 Qualitative Synthesis

The 19 identified articles were published between 2008 and 2021. Four of the 19 studies (21.05%) evaluated the effect of sports on EFs for only one gender (Nakamoto & Mori, 2008; Waelle et al., 2021; Yamashiro et al., 2015).

One of the 19 studies examined children (5.26%), one studied preadolescent (5.26%), one studied adolescents and adults (5.26%), ten studied the EFs of only adult athletes (52.63%), and seven studied older adults (36.84%). The characterisation of included studies is displayed in Table 1.

Inhibitory control (IC) was examined in 12 studies (63.15%), working memory (WM) was assessed in eight studies (42.11%), and cognitive flexibility (CF) was evaluated in six studies (40%). The authors used various tasks to measure EFs. The most commonly used tasks were Stroop Task (for IC), Ericsen Flanker Task (for IC), Visuospatial memory task (for WM), n-Back task (for WM), and Trail-making task (for CF).

The sport modes that were compared in the studies are displayed in Table 2. The most frequently evaluated sports for OSE were tennis (18.18%), table tennis (18.18%), and badminton (13.64%), and that for CSE were swimming (32.61%), running (26.09%), and athletics (15.22%). 14 of the included studies used a controlled design (73.68%), while five studies did not use any control group in their study (26.32%, see Table 1). One study evaluated differences after the completion of hours of training per week (Ballester et al., 2019;) and an International Physical Activity Questionnaire (IPAQ; examines exercise behaviour and time spent sitting), and reported superior performance by the CSE group (Chen et al., 2019). In three articles, comparison of the level of performance or experience between the two groups was not entirely reported (Koch & Krenn, 2021; Nakamoto & Mori, 2008; Yamashiro et al., 2015). Fourteen studies reported that the OSE and CSE groups did not show any difference in their level of performance or sports experience.

Ten of the included studies (52.63%) concurred with the postulation of previous studies that OSE athletes show superior EFs when compared to CSE athletes. The findings of five studies (26.32%) were inconsistent. Four studies (21.05%) could not show superiority of neither OSE nor CSE athletes, with regards to better EFs.

3.3 Quantitative Synthesis

Overall Analysis. The random effect model (k = 19), which included all studies with combined effect sizes showed an estimated overall effect size of 0.174 (95% CI [-0.067, 0.415]; SE = 0.119; Fig. 3). The estimated effect was not significant (p = .157). The analysis of heterogeneity was also not significant (Q(19) = 2.257; p = 1.000; Tau^2 = 0.000; I^2 = 0%; H^2 = 1.000). The lowest effect sizes were negative (g = -0.15 to -0.03, favouring CSE). The highest effect sizes of the model reached g = 0.47 to 0.65. The results of the overall meta-analysis are displayed in the Forest plot in Figure 2. Calendar age was not a moderator in the analysis (Mixed model effect: -0.002; p = 0.686; 95% CI

[-0.012, 0.008]; SE = 0.005). Study quality was also not a significant moderator of the meta-analysis (Mixed model effect: -0.037; p = 0.818; 95% CI [-0.356, 0.282]; SE = 0.163).

Subgroup Analysis. In the subgroup analysis, the effect size of random effects model of the three EFs (inhibitory control, working memory, cognitive flexibility) were calculated independently. The results of this analysis are shown in the Forest plot in Figure 4.

The random effect model for the studies evaluating the effect of OSE versus CSE participation on inhibitory control (k = 11) revealed an overall effect size of g = 0.191 (95% CI [-0.117, 0.500]; SE = 0.157). Heterogeneity analysis showed no significant results (Q(10) = 0.773; p = 1.000; Tau^2 = 0.000; I^2 = 0%; H^2 = 1.000). Calendar age did not affect subgroup analysis for inhibitory control (Mixed model effect: -0.003; SE = 0.006; p = 0.679).

The effect of subgroup analysis of working memory revealed an overall effect size of 0.138 (p = 0.474; 95% CI [-0.240, 0.516]; SE = 0.193). Analysis of heterogeneity of subgroup analysis returned a small value (Q(6) = 1.793; p = .938; Tau^2 = 0.000; I^2 = 0%; H^2 = 1.000). Calendar age did not affect subgroup analysis for inhibitory control (Mixed model effect: -0.001; SE = 0.008; p = 0.895).

The effect size estimate of the cognitive flexibility of OSE and CSE athletes was not significant (g = 0.210 p = 0.276; 95% CI [-0.168, 0.587]; SE = 0.193). Analysis of heterogeneity of subgroup analysis returned a small value (Q(7) = 0.519; p = .999; Tau^2 = 0.000; I^2 = 0%; H^2 = 1.000). The moderating effect of calendar age on overall effect size with respect to cognitive flexibility was -0.005 (SE = 0.008; p = 0.505).

The funnel plot analysis (Figure 3) did not indicate publication bias for overall and subgroup effect size estimates. An asymmetry in data points could not be determined with respect to the overall effect. No effect size or SE exceeded the 95%

confidence interval. Furthermore, no specific gap in the variation of studies could be identified.

5 Discussion

The current systematical review and meta-analysis aimed to assess the overall effect of the impact of OSE and CSE participation (categories 1–4) on EF performance. To the best of our knowledge, this is the first qualitative and quantitative synthesis of studies that analyses the effect of sport modes on EFs only. Furthermore, previous reviews did not focus on the characteristics of examined sport types. The subgroup analysis is updated with the latest research on the effects of different sport modes on the expression of EFs (inhibitory control, working memory, cognitive flexibility). An important question regarding the sport mode is, which classification of sport types is applied to describe differences in cognitive functions. In previous studies, bivariate comparison between open-skill and closed-skill sports was dominant (with redundant or similar bivariate division into external and self-paced sports). Yongtawee et al. (2021) and Krenn et al. (2018) suggested a tripartite classification. We applied our own characterisation for the current study to describe the variance between sport modes more precisely using four categories.

5.1 Qualitative Synthesis

As far as qualitative synthesis is concerned, relatively few studies had samples with a low average calendar age (children, adolescents). However, this is important because, it is at this age, that the formation of EFs is highly relevant, and so should be recorded and researched with reference to longitudinal studies (Ludyga et al., 2021).

The studied sport modes did not vary widely. Most frequently used sports had similar characteristics. This applies to both OSE and CSE. The studies lacked a detailed description and sport mode-specific interpretation of results. The qualitative analysis revealed that OSE was evidently superior to CSE in terms of EFs, as proved by10 out of 19 studies, which showed positive effects.

The frequently examined OSEs such as tennis, table tennis, and badminton were classified into category 4, which requires high cognitive requirements, variable environmental conditions, and erratic movements. In contrast, the commonly examined CSEs, such as swimming and running, which do not require high cognitive functions, were classified into category 1. Thus, the effect of CSE vs. OSE could be overestimated in a narrow sense.

5.2 Quantitative Synthesis

Overall Analysis. The broad skill transfer hypothesis, which is the suggested theory to explain the phenomena occurring in this context, argues that training in sports or cognitive tasks may increase performance in related but untrained tasks (Furley & Memmert, 2011; Taatgen, 2013). Recent studies confirm this theory. For example, Jacobson and Matthaeus (2014) postulate that OSE athletes are superior in EFs than CSE athletes because they are trained better in the relevant cognitive performances. The overall analysis of effect sizes calculated to determine the difference in EF measures between OSE and CSE athletes were indicated as low (g = 0.174; p = .157) and not significant. Based on the proven homogeneity of the studies, it can be concluded that OSE athletes have moderate advantages over CSE athletes in their executive functions. This finding also coincides with the results of the studies by Gu et al. (2019) and Zhu et al. (2020). The analysis of further studies has expanded the evidence. The overall effect size could be confounded by the selection of sport modes and the design of the study. This stands to reason that studies that analyse differences in EFs in sports such as badminton and swimming can show high effect sizes or mean differences.

5.2 Characterisation of Examined Sport Modes

It is particularly striking that the five studies with the smallest effect sizes (Chueh et al., 2017; Dai et al., 2013; Guo et al., 2016; Huang et al., 2014; Tsai & Wang, 2015) show the difference between OSE sports such as tennis, table tennis and badminton (category 4) and CSE sports such as swimming, running and triathlon (category 1). The OSE sports considered in this case were racket games, which were characterised by one or two opponents at the maximum. The studies with the highest effect sizes (Chen et al., 2019; Koch & Krenn, 2021; Nakamoto & Mori, 2008; Yamashiro et al., 2015; Yu et al., 2017) compared various OSE sports such as basketball, canoe slalom, handball, Olympic sailing, and baseball with two or more CSE sports such as archery, cross-country skiing, shooting, speed-skating, and weightlifting. Even though these studies have sample sizes exceeding the value of 75 ($n>75$), the mixing of many sports into groups could lead to an opaque attribution of the effects (Krenn et al., 2018). The hypothesis that effect sizes of studies comparing athletes of sports categories 2 and 3 are smaller than those comparing athletes in sports categories 1 and 4 had to be rejected. Differences in effect size could not be explained by the selected sport mode. Therefore, at this point, further research is needed to arrive at a strong conclusion.

Subgroup Analysis. One area in which previous studies lacked is that they did not calculate the effect of the sports on working memory in an independent manner. The subfunction or subgroup analysis studied visuospatial attention and processing speed, instead of working memory (Zhu et al., 2020). The subgroup analysis of the current study shows differences in the effect size between the three EFs (CF: $g = .210$ > IC: $g = .191$ > WM: $g = .138$). The different affordances may explain this order of effect of OSE for CF, IC, and WM. It could be speculated that OSE athletes often have to switch between strategies or tasks (Dai et al., 2013) and inhibit irrelevant information (Huijgen et al., 2015).

5 Conclusions

This current meta-analysis could not validate the hypothesis that sport modes examined in the included studies representing low to moderate effect sizes have similar cognitive demands. However, the commonly examined sport modes differ with respect to demands of skills. The design of the current study does not lend to the investigation of this research question to the fullest extent. Given this drawback, it is quite probable that the overall effect was overestimated. In this context, Krenn et al. (2018) suggested in their article that future researches must study different cognitive demands in OSE and CSE. The results of the current meta-analysis suggest a completely new approach to this issue. Future research has to classify the included sport modes based on their cognitive demands, to prove the broad skill transfer hypothesis in this context. Simple differentiation between OSE and CSE cannot pave way for further inferences in this field. The presented classification is suggested for future research. A conceivable study design could examine EFs in two sport modes of OSE and CSE, with differing cognitive demands or skills. In this case, OSE with low demands should not differ from CSE with high cognitive affordances (i.e., sports of mentioned category 2 and 3: athletics vs. alpine skiing). Considering the different effect sizes for the impact of affordances in sport on IC, WM, and CF, it is helpful to implement tasks for these three parts in future research. This approach can determine as to what extent these differences can be empirically proven.

Table 1

Characteristics of the cross-sectional studies eligible for qualitative and quantitative analysis (alphabetical order)

Study (Author, Year)	**Sample Size** Total OSE CSE Control **(Female/male)**	**Sample Age in Years** OSE CSE, Control **(M/SD)** **(Age Category)**	**EFs**	**EF-measure**	**OSE**	**CSE**	**Level of performance / Experience**	**Outcome** Regarding the difference between OSE vs. CSE
Ballester et al. 2019	*N* = 66 22 (8/14) 22 (10/12) 22 (--/--)	24.6 (0.9) 22.5 (0.9) 22.3 (0.6) (Adults)	IC	Oddball Task	Basketball, Football, Martial arts, Tennis, Volleyball	Athletics, Cycling, Swimming Triathlon	No differences in years of training (p = .285) but in hours per week (*p* = .019, *d* = .75, OSE < CSE)	- Sig. effect of type of sport on inhibition control (OSE > CSE)
Chang et al. 2017	*N* = 60 20 (5/15) 20 (6/14) 20 (7/13)	21.15 (1.2) 21.20 (1.8) 21.60 (1.4) (Adults)	IC, CF	Stroop Task, WCST	Wushu training	Marathon running	No differences in training hours and training years between OSE and CSE, national level	- No sig. effects between groups in Stroop or WCST performance (OSE > CSE)
Chen et al. 2019	*N* = 60 23 (4/19) 24 (15/9) 23 (11/12)	57.17 (3.2) 59.08 (7.2) 58.91 (4.8) (Adults)	WM	Spatial Working Memory Task	Badminton, Basketball, Table tennis, Tennis	Cycling, Running, Swimming	Sig. difference in IPAQ (*F*[2,67] = 8.30, p < .001, mean IPAQ scores: CSE > OSE > control)	- Sig. main effects of group (*F*[2,67] = 5.73, *p* < .01, η_p^2 = 0.15) for accuracy but no difference between OSE and CSE (*ps* < .05) - No sig. main effects for RT for group (*F*[2,67] = 0.69, *p* > 0.05, η_p^2 = 0.02)

Chueh et al. 2017	N = 48 16 (7/9) 16 (7/9) 16 (7/9)	20.00 (1.2) 21.10 (2.3) 20.70 (1.1) (Adults)	WM	Non-delayed and delayed match-to-sample task	Badminton, Table tennis	Running, Swimming, Triathlon	Differences in years of training between OSE (10.8 ± 2.2) and CSE (9.7 ± 3.2)	- No main effects of group for accuracy results (F[2,45] = 0.025, p = .096) - Sig. effects of group for RT results (F[2,45] = 5.11, p < .05, η^2 = .185) but no sig. effects between OSE and CSE groups (OSE: 632.52 ms; CSE 655.03 ms < Con: 736.66 ms)
Dai et al. 2013	N = 48 16 (7/9) 16 (10/6) 16 (14/2)	69.00 (3.6) 69.90 (3.6) 67.30 (3.0) (Older Adults)	CF	Task-switching paradigm	Table tennis, Tennis	Running, Swimming	Differences in years of training between OSE (13.0 ± 5.7) and CSE (11.1 ± 5.4)	- Sig. differences for RT compared with control group (ts (30) > 2.46, p < .02) for homogeneous condition, no sig. differences between OSE and CSE - Sig. main effect for exercise mode for global switch costs (F[2,45] = 3.52, p = .03, η^2 = .14) with differences between OSE and CSE but not for local switch cost (F[2,45] = .20, p = .82)
DeWaelle et al. 2021	N = 170 86 (86/--) 25 (25/--) 59 (59/--)	10.20 (1.0) 10.30 (1.1) 10.40 (1.1) (Children)	IC, WM	Spatial Span Task, Token Search, Monkey Ladder, Double Trouble Task, Sustained Attention to Response Task	Basketball, Hockey, Korfball, Soccer, Volleyball	Athletics, Cycling, Swimming,	At least 2 h/week, no differences between OSE and CSE	- Sig. main effect for group (F[2,166] = 5.143, p = .007, η_p^2 = .058) with superior executive functions of OSE compared with CSE and control group
Gökce et al. 2021	N = 54 18 (9/9) 18 (9/9) 18 (11/7)	20.44 (1.9) 21.00 (2.0) 22.33 (1.9)	WM	Corsi's Block Tapping Test	Fencing	Swimming	No sig. differences in training history between OSE group	- Sig. differences for right- and left-handed CBT, left hemispace accuracy was significantly different

		(Adults)					(8.27 ± 2.13 years) and CSE group (8.22 ± 2.66 years)	among the groups (right: $H(2) = 15.336$, $p < .001$, $\eta^2 = .28$; left: $H(2) = 12.318$, p = .002, $\eta 2 = .23$) - OSE higher than CSE($p = 0.034$, $r = -0.41$) and controls ($p < .001$, $r = -0.65$) - Both OSE ($p = .017$, $r = -.46$) and CSE ($p = .003$, $r = -0.53$) higher accuracy scores than controls
Guo et al. 2016	$N = 111$ 36 (19/17) 38 (23/15) 37 (21/16)	67.6 (5.9) 66.7 (5.8) 66.9 (5.9) (Older Adults)	WM	Visuospatial WM, short-term memory & mental rotation task	Badminton Table Tennis	Running, Swimming	No differences in training hours and training years between OSE and CSE	- Sig. effect of group on short-term memory task accuracy ($F(2, 99) = 3.68$, $p = .02$), but no differences between OSE and CSE - No sig. differences in reaction time among the groups ($F(2, 99) = 0.54$ $p = .58$)
Holfelder et al. 2021	$N = 86$ 46 (23/23) 40 (20/20)	13.85 (0.7) 14.05 (0.8) (Preadolescents)	IC, WM, CF	Flanker Task, n-Back Task, Trail Making Task	Handball	Athletics	Amateur and elite athletes of OSE and CSE	- No effect of type of sport on working memory, inhibitory control or cognitive flexibility - specific Trail Walking Task sig. group effect ($p < .01$; no standard EF-measure)
Huang et al. 2014	$N = 60$ 20 (9/11) 20 (11/9) 20 /14/6)	69.4 (3.0) 70.55 (2.6) 68.3 (2.3) (Older Adults)	IC	Ericsen Flanker Task	Table Tennis, Tennis, Badminton	Running, Swimming	Differences in participation regularity (OSE > CSE), exercise duration (OSE > CSE) and weekly frequency (OSE < CSE)	- Sig. effect of goup on inhibition control ($F(2,57) = 3.33$, $p = .043$) - OSE (441.94 ms) and CSE athletes (446.45 ms) exhibiting shorter RTs than controls (476.11 ms)

Jacobson & Matteaus 2014	N = 54 22 (8/14) 17 (14/3) 15 (9/6)	20.05 (1.2) 20.18 (1.5) 20.20 (1.3) (Adults)	IC	D-KEFS Tower Test & Color-Word interference Test	Soccer, Tennis	Running, Swimming	Differences between high-skilled and recreational Athletes	- Sig. effect of group on inhibition control ($t(52)$ = 2.94, p = .003, r = .37); OSE > CSE
Koch & Krenn 2021	N = 75 44(18/26) 31(12/19) -	22.89 (4.2) 23.23 (4.7) (Adults)	WM, IC, CF	Design Fluency Test, Trail Making Task, Flanker Task, 2-back Task	American football, Basketball, Canoe slalom, Handball, Olympic sailing	Archery, Athletics, Cross-country skiing, Marathon, Shooting, Swimming, Track-bike, Triathlon	Elite athletes	- Sig. main effect of group on cognitive flexibility ($F(3, 70)$ = 2.55, p = .03) and working memory ($F(3, 70)$ = 3.05, p = .02); OSE > CSE
Li et al. 2018	N = 75 25 (10/15) 25 (17/8) 25 (21/4)	69.04 (3.4) 69.80 (3.1) 67.80 (2.9) (Older Adults)	IC, CF	Stroop Task, Task-switching	Table tennis, tennis	Running, Brisk walking	No differences in physical activity in exercise groups	- Sig. effect of group on inhibition control ($F(2,66)$ = 4.60, p = .013) and global switch costs in task switching ($F(2,24)$ = 7.03, p = .004) - No reported difference between OSE and CSE
Nakamoto & Mori 2008	N = *18* 9 (--/9) 9 (--/9)	--	IC	Go/NoGo Task	Baseball	Athletics, Gymnastics	OSE group spent 25 h/week for baseball training, no data for CSE group	- No significant group difference ($t(16)$=1.65, p < .05) for simple reaction time - Sig. group differences for Spatial-BB, Spatial-Mix and color condition(p < .01)
Tsai & Wang 2015	N = 64 21 (7/14) 22 (8/14) 21 (8/13)	65.35 (4.2) 66.03 (4.1) 63.94 (3.4) (Older Adults)	CF	Task switching	Badminton, Tabletennis	Running, Swimming	No differences in training (3 x 30 min/week) and training years (2 years)	- OSE responded faster in switch condition than CSE - sig. main effect of group on specific RT switch costs (F[2,61] = 7.30, p = .001) -

Wang & Guo 2020	N = 259 85 (45/40) 87 (49/38) 87 (46/41)	66.8 (5.5) 65.5 (5.8) 65.9 (6.3) (Older Adults)	IC	Attention network test (ANT)	Badminton, Tennis	Running, Swimming	No differences in training (3 x 30 min/week) and training years (1 year)	- OSE significantly higher executive network efficiency than CSE (p < .01) - No differences for alerting and orienting networks (p > .05) and for proportion scores of alerting and orienting networks
Wang et al. 2013	N = 60 20 (-/20) 20 (-/20) 20 (-/20)	20.70 (2.4) 19.31 (0.8) 20.40 (2.1) (Adolescents/Adults)	IC	Stop-signal task	Tennis	Swimming	No sig. differences [t(39) =.89, p= .381, d= 0.28] in years of training between OSE (5.50 ± 2.80) and CSE (4.85 ± 1.64)	- OSE had shorter stop-signal reaction times than CSE (t(39) = 3.76, p = .001) - no differences on RTs between OSE and CSE - No significant differences among groups on inhibition function (F(2, 57) = .02, p = .981, η_p^2 =.00)
Yamashiro et al. 2015	N = 24 12 (-/12) 12 (-/12) --	21.2 (0.8) 22.7 (3.4) -- (Adults)	IC	Go/Nogo paradigm	Basketball	Athletics, Swimming	No differences	- Go/Nogo RT shorter for OSE than CSE (p = .07).
Yu et al. 2019	N = 54 18 (8/10) 18 (7/11) 18 (9/9)	21.1 (2.2) 21.1 (2.2) 21.8 (2.1) (Adults)	CF	Cued task-switching paradigm task	Badminton	Athletics	No differences in years of training levels of skill competencies between OSE and CSE	- sig. fewer switch costs in OSE than CSE in 100% validity condition (p = .023) - No significant differences in switch costs between OSE and CSE (p = .473)

Note: EFs = Executive Functions, OSE = Open-Skill-Exercise, CSE = Closed-Skill-Exercise, WM = Working-Memory, IC = Inhibition Control, CF = Cognitive Flexibility, RT = reaction time, ACC = accuracy

Table 2

Frequency and percentages of OSE and CSE examined and compared in the included studies

OSE	Classification	Frequency *N* = 44	Percentage [%]	CSE	Classification	Frequency *N* = 46	Percentage [%]
Tennis	4	8	18,18	Swimming	1	15	32,61
Table Tennis	4	8	18,18	Running	1	12	26,09
Badminton	4	6	13,64	Athletics	2	7	15,22
Basketball	4	5	11,36	Triathlon	1	3	6,52
Volleyball/Beach volleyball	4	2	4,55	Cycling	1	3	6,52
Soccer	4	3	6,82	Gymnastics	1	1	2,17
Handball	4	2	4,55	Archery	1	1	2,17
Sailing	3	2	4,55	Shooting	1	1	2,17
American Football	4	1	2,27	Brisk walking	1	1	2,17
Wushu	4	1	2,27	Cross-country skiing	2	1	2,17
Martial Arts	4	1	2,27	Track-bike	1	1	2,17
Fencing	4	1	2,27				
Korfball	4	1	2,27				
Hockey	4	1	2,27				
Canoe slalom	3	1	2,27				
Baseball	4	1	2,27				

Figure 1

PRISMA-Flowchart of the study selection process

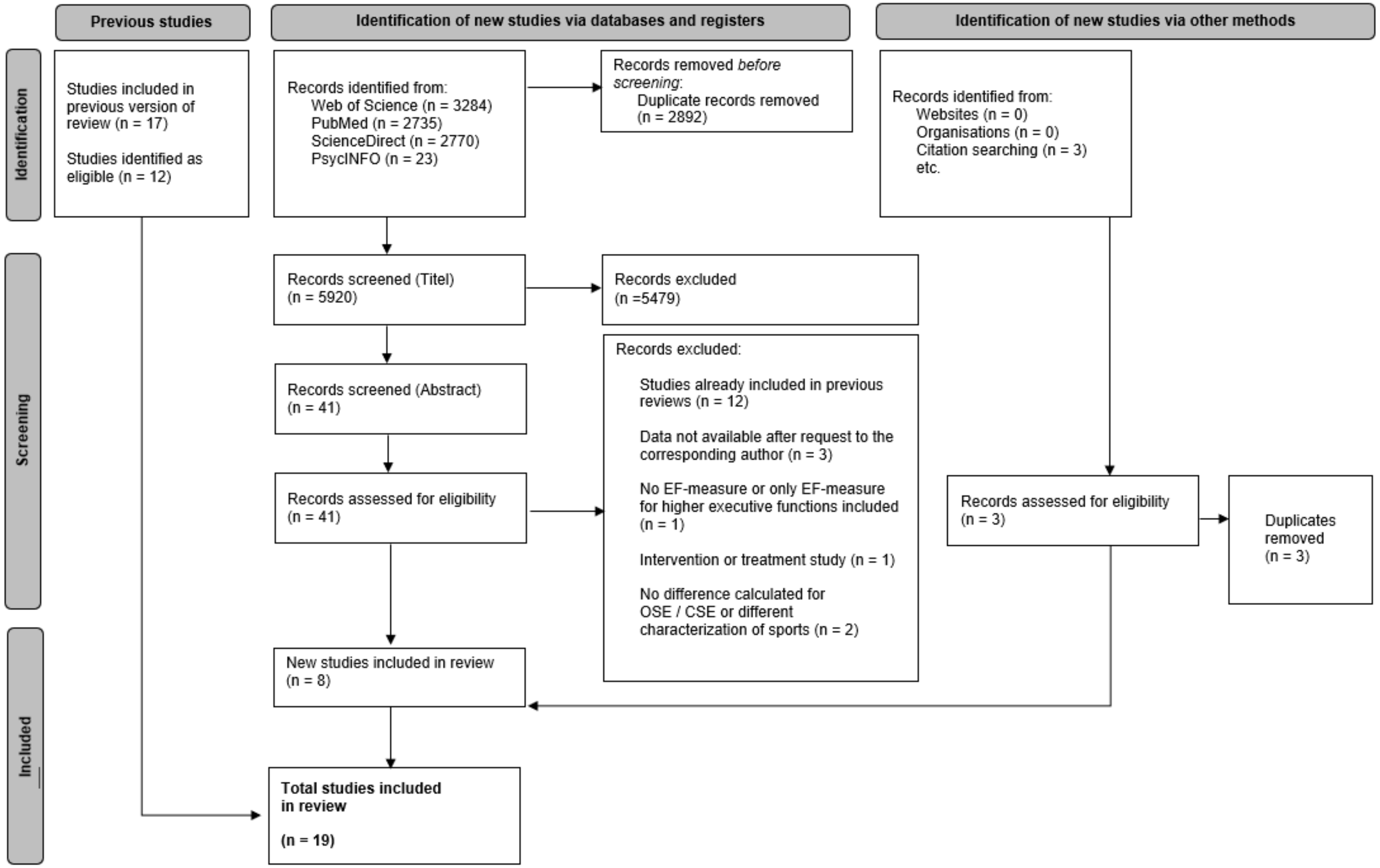


Figure 2

Forest plot for the efficacy of OSE compared to CSE (ordered according to the specified effect size)

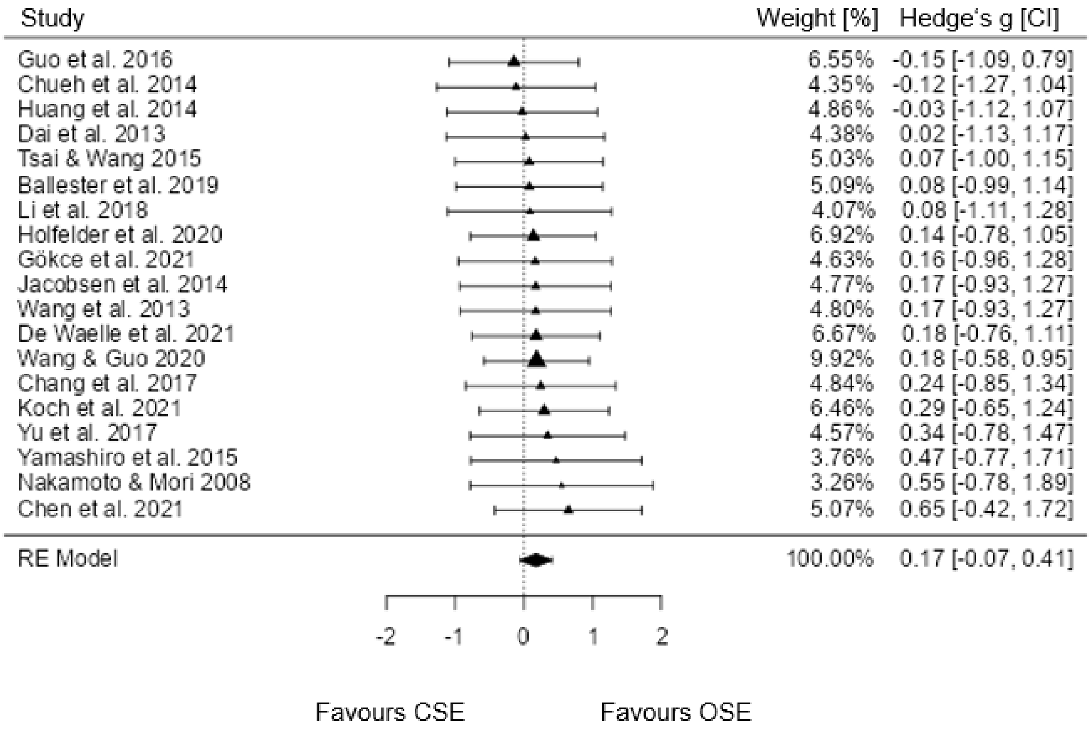


Figure 3

Funnel plot for estimating the publication bias of overall and subgroup quantitative synthesis

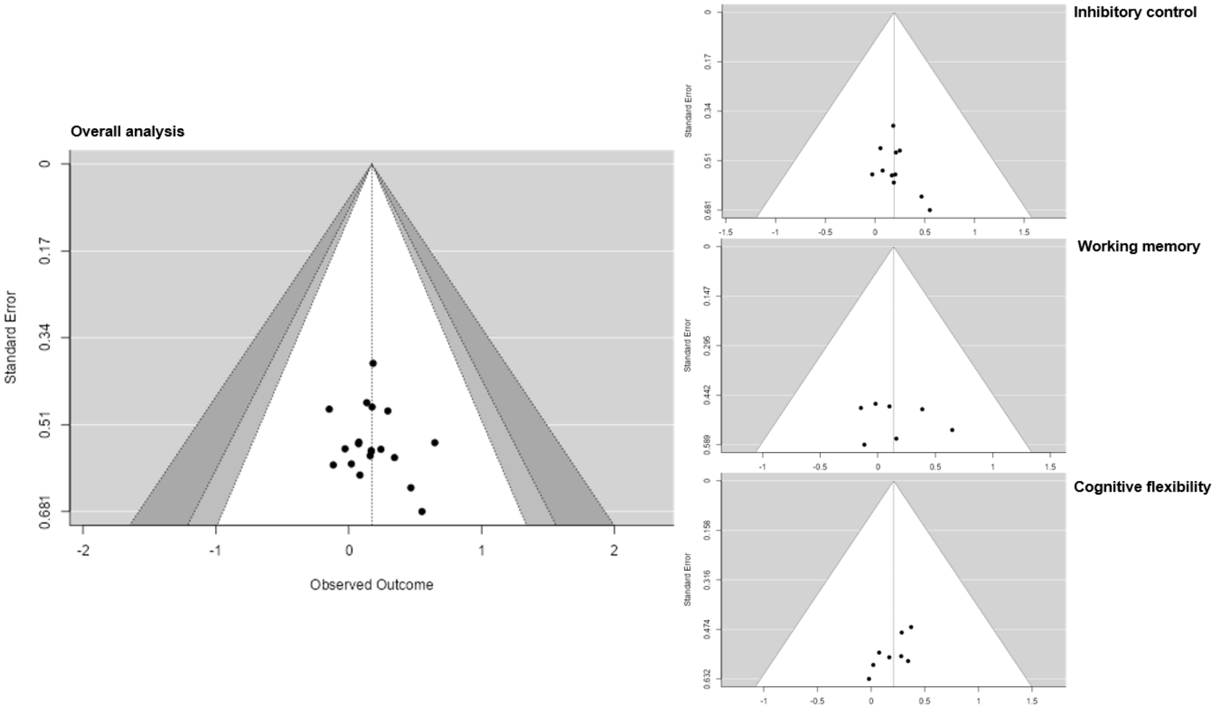
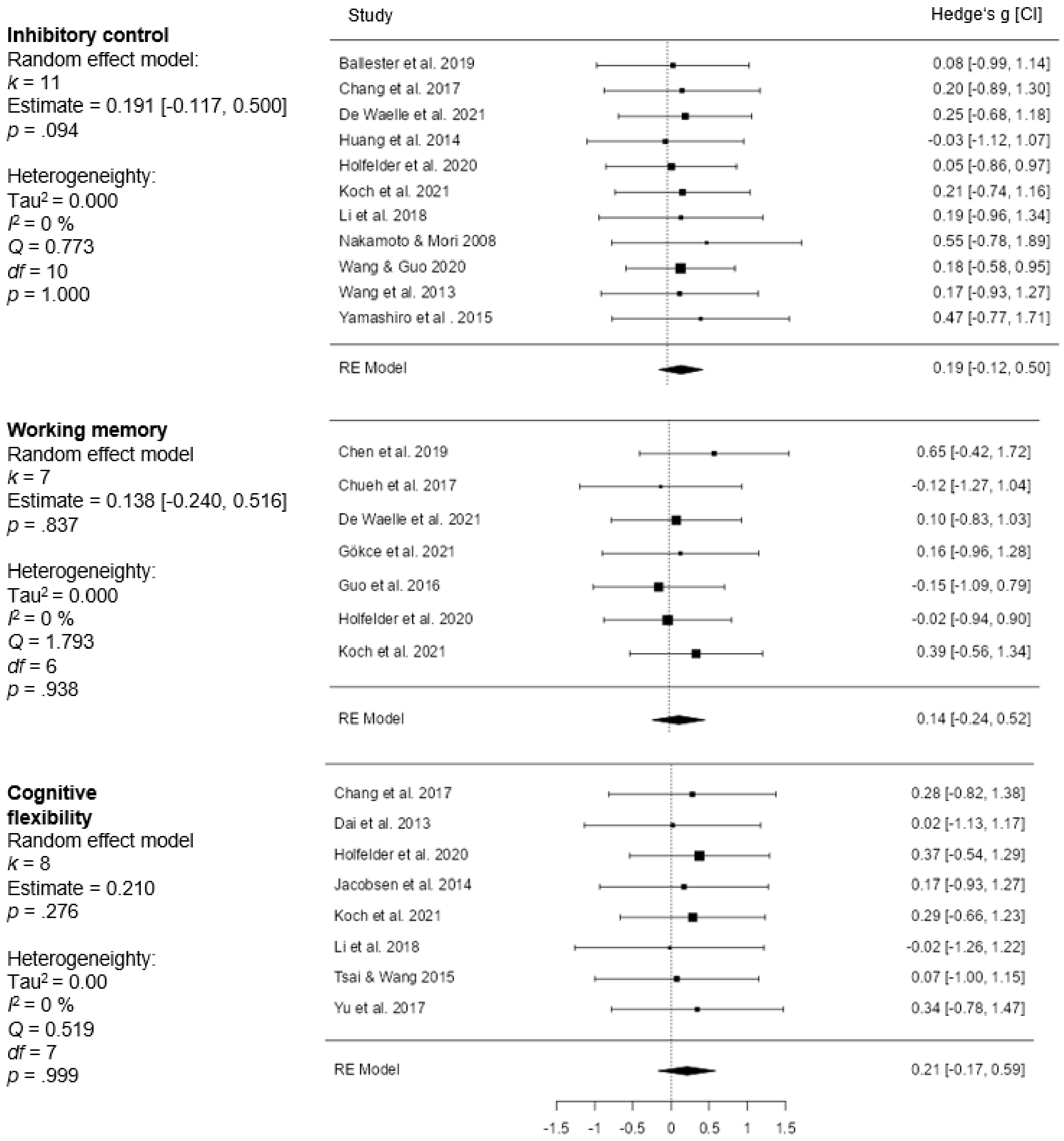


Figure 4

Forest plots of subgroup analysis (OSE vs. CSE)



Appendix A

Search term:

("executive function"[MeSH Terms] OR ("executive"[All Fields] AND "function"[All Fields]) OR "executive function"[All Fields] OR ("executive"[All Fields] AND "functions"[All Fields]) OR "executive functions"[All Fields]) AND ((open[All Fields] AND skill[All Fields]) OR (closed[All Fields] AND skill[All Fields]) OR (("exercise"[MeSH Terms] OR "exercise"[All Fields]) AND mode[All Fields])) AND ("sports"[MeSH Terms] OR "sports"[All Fields] OR "sport"[All Fields]) AND ("2000/01/01"[PubDate] : "2021/12/31"[PubDate]) AND ("2000/01/01"[PubDate] : "2021/12/31"[PubDate])

Data Availability

The data that support the findings of this study are available from the corresponding author (F.H.), upon reasonable request.

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