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The impact of a single bout of high-intensity interval exercise on executive function in adolescents and young adults: A systematic review and meta-analysis

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Abstract

Objective: Cognitive function is a critical developmental indicator in adolescents and young adults, and physical activity has been shown to enhance cognitive abilities. However, the effects of high-intensity interval exercise on cognitive function in adolescents and young adults remain unclear**. Methods:** A literature review was conducted, with systematic searches across three databases. Two researchers independently screened the studies based on inclusion criteria, assessed the risk of bias, and, following the organization of relevant literature, performed a Meta-analysis using RevMan 5.4 software. **Results:** Based on 13 studies involving 559 adolescents, the meta-analysis revealed distinct outcomes depending on the study design. In single-arm studies, acute high-intensity interval exercise significantly improved Stroop Task reaction time (WMD = -1.47, $P < 0.00001$), with subgroup analyses suggesting that cycling interventions lasting 30 minutes were most effective. However, these studies also showed a significant decrease in the number of correct responses ($P = 0.0003$). In contrast, randomized controlled trials (RCTs) observed no significant improvement in reaction time ($P = 0.62$). **Conclusion:** High-intensity interval exercise interventions in adolescents and young adults were associated with enhanced reaction speed and information processing capacity; however, no improvements have been observed in accuracy. The effects on cognitive control require further investigation.

Keywords: high-intensity interval exercise; adolescents and young adults; Cognitive Function; Meta-analysis

1. Introduction

Cognitive function (CF) refers to the mental processes that support perception, memory, reasoning, and action[1]. While cognitive tasks are generally categorized into two main types—basic information processing and executive function (EF)[2]—it is essential to emphasize that these tasks exist on a continuum. At one end are tasks primarily involving basic information processing, while at the other end are more complex tasks requiring significant executive function support. Basic information processing demands fewer cognitive resources, representing lower-level cognitive functions, such as simple motor speed or information processing tasks[3]. In contrast, executive functions are higher-order cognitive

processes that enable purposeful, goal-directed behavior. Executive function comprises three core dimensions that are crucial for tasks such as planning, problem-solving, and learning: inhibitory control, working memory, and cognitive flexibility. Research has demonstrated that executive function plays a pivotal role in academic, professional, and everyday success[4].To date, numerous studies have shown that physical activity has a more pronounced effect on high-level executive function tasks than on tasks requiring less cognitive effort. Recent systematic reviews of studies involving school-age children and adolescents and young adults[5], as well as research on older adults[6], indicate that vigorous physical activity has a more significant impact on cognitive ability than moderate or low-intensity exercise. Furthermore, regular participation in physical activity offers important benefits for physical health, including improved cardiorespiratory fitness (CRF), muscle health, and better body composition. Substantial evidence suggests that adolescents and young adults should engage in vigorous physical activities, as these activities provide greater health benefits compared to lower-intensity activities[7,8].

High-intensity interval Exercise (HIIE) is a form of exercise that alternates between short bursts of high-intensity effort and brief periods of low-intensity exercise or rest[9]. HIIE is commonly implemented in research through activities such as running or cycling[10]. As an alternative to moderate-intensity continuous exercise or resistance training, HIIE not only promotes improvements in various health indicators, including aerobic capacity[11], lipid metabolism[12], vascular function[13], and balance[14] but also increases muscle mass and strength, thereby enhancing athletic performance[15,16]. It also has a positive impact on mental health[17]. A recent scientific report from the 2018 HIIE Activity Guidelines Advisory Committee emphasized that HIIE has emerged as an innovative and effective strategy to improve health-related physical fitness in adolescents and young adults[10,18]. In addition to these physiological benefits, HIIE has also been shown to enhance cognitive function[19].

HIIE can improve brain blood flow, neuroplasticity, and metabolic health[20,21]. HIIE has been found to improve attention, information processing speed, and memory function. Compared to traditional moderate-intensity continuous exercise, HIIE may provide similar or even more significant cognitive benefits in a shorter duration[22–24]. However, research on the effects of HIIE on adolescent cognitive function and executive function remains relatively limited, and further investigation is warranted.

Acute exercise (AE), or a single bout of exercise, has gained considerable attention in recent years due to its positive effects on cognitive function[25]. According to guidelines from the American College of Sports Medicine (ACSM, 2020) and various national physical activity recommendations, the benefits of acute exercise for cognitive function are widely acknowledged[26]. Multiple studies have shown that a single session of exercise is significantly positively correlated with various cognitive functions, such as attention, information processing speed, and memory, and has profound effects on executive functions[27–29]. Existing research suggests that acute exercise can effectively enhance performance in executive functions[30–32]and positively modulate neural electrical activity[33]as well as neural network functioning[34]related to tasks requiring executive function. However, the specific mechanisms through which HIIE influences executive function remain to be fully understood.

Previous reviews have explored the impact of HIIE on cognitive functions and mental health outcomes in different populations[35–37]. However, adolescence is a critical period during which the brain undergoes significant functional and structural changes[38], leading to considerable individual differences in cognitive abilities. Additionally, acute exercise and chronic exercise interventions have distinct effects on cognitive function. Adolescents and young adults typically refer to individuals aged 12-18 years, who are in the stage of puberty and undergoing rapid changes in physical, psychological, and social roles[39]. Young adults,

on the other hand, are generally considered to be between the ages of 18-25, or extending up to 30 years, and are in the stage of emerging adulthood. This period is characterized by the exploration of identity, independence, and social roles[40]. During the transition from adolescence to young adulthood, an individual's executive functions (such as attention, working memory, and inhibitory control) and cognitive control abilities remain highly plastic[41,42]. Individuals in this phase are still in a process of continual development and improvement of cognitive abilities, particularly when faced with complex decision-making and multitasking[43]. Therefore, in this study, the target population is defined as "adolescents and young adults."

Although there are clinical trials investigating the acute effects of HIIE on cognitive function in adolescents and young adults, this area has not yet been summarized through a meta-analysis to enhance the strength of evidence from the research findings. Therefore, this review aims to evaluate the impact of a single bout of HIIE on adolescent cognitive function using a systematic review and meta-analysis approach. Furthermore, it seeks to explore potential factors influencing these effects, such as study design, duration of interventions, participant age, HIIE content, control group design, and risk of bias.

2. Materials and Methods

This systematic review was designed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[44], and the literature search and selection process followed the Cochrane systematic review guidelines[45]. The study was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO) under trial registration number CRD42025630839 and reported in compliance with PRISMA guidelines.

2.1 Inclusion Criteria

Studies included in this review were selected based on the PICOS framework (Population, Intervention, Comparison, Outcome, Study design), which defines the research subjects, interventions, control measures, outcome indicators, and study types. Within the study design component of this framework, the investigations encompassed randomized controlled trials, randomized crossover trials, and single-arm studies. A single-arm study is a type of clinical trial design in which all participants receive the same intervention without the inclusion of a control group[46]. Detailed information is provided in Table 1.

2.2 Exclusion Criteria

The exclusion criteria were as follows:①Studies not involving HIIE or related training;②Studies involving populations other than healthy adolescents and young adults;③Primary studies from which data could not be extracted;④Reviews, meta-analyses, conference abstracts, and theses (Master's or Doctoral);⑤Studies where the full text was not accessible;⑥Studies that had been published multiple times.

2.3 Literature Search

The literature search was conducted following the PICOS criteria. To ensure comprehensive coverage of relevant studies, multiple databases were used, including PubMed, Web of Science, and the Cochrane Library. In addition to the initial search for original literature, a second round of searches was performed for the included studies to identify any potentially missed articles. Efforts were also made to include relevant literature from various other sources. To ensure the thoroughness and reliability of the search, both controlled vocabulary and free-text terms were combined, with appropriate search methods applied for each database. The retrieval strategy is provided in the attachment.

2.4 Literature Screening and Data Extraction

Two researchers independently screened the retrieved studies and cross-checked their selections for accuracy and reliability. Endnote software was used to manage the included

studies, eliminating duplicates and irrelevant studies during the initial screening. Titles and abstracts were reviewed to exclude clearly irrelevant studies. For studies where the relevance was uncertain, full-text articles were reviewed to further assess their suitability. Only studies meeting the criteria for systematic reviews and meta-analysis were included. In case of disagreement, the researchers discussed the discrepancies and consulted a third researcher if needed. The reasons for inclusion or exclusion of studies were meticulously recorded to ensure transparency.

Data extraction was independently performed by two researchers, with verification of the extracted data. The data collected included the following: first author's full name, publication year, study design, characteristics of the study population (age, physical condition), group characteristics, intervention duration, intervention content for both the experimental and control groups and primary outcome measures. For studies with multiple groups, data corresponding to the relevant groups were extracted. In studies without grouping, baseline data before the intervention and post-intervention data were extracted. If any study lacked data, the authors were contacted by email to request the necessary information. If data could not be obtained, the study was excluded from the analysis.

2.5 Quality Assessment of the Studies

The quality of the included studies was assessed using the MINORS (Methodological Index for Non-Randomized Studies) scale[47]and the Cochrane risk of bias tool[48]. Two researchers independently evaluated the quality of the studies, and in case of discrepancies, discussions were held with a third researcher to reach a consensus. The MINORS scale is used to assess the methodological and reporting quality of non-randomized controlled trials (non-RCTs). The scale scores are set as 0 (not reported), 1 (reported but insufficiently), or 2 (reported adequately). Higher scores indicate better quality. The Cochrane risk of bias tool categorizes risks into high, medium, or low, with results visualized in a chart for clearer assessment.

2.6 Statistical Analysis

Statistical analyses were performed using Review Manager (RevMan 5.4) software. The analysis considered effect sizes, using weighted mean difference (WMD) for continuous outcomes and standardized mean difference (SMD) for outcomes with different units. The 95% confidence intervals (CIs) were calculated, with a significance level set at $P < 0.05$. To evaluate heterogeneity, the Chi-square test and I^2 statistic were applied. If $P > 0.1$ and $I^2 \leq 50\%$, no significant heterogeneity was assumed between studies, and a fixed-effect model was used. If $P \leq 0.1$ and $I^2 > 50\%$, significant heterogeneity was assumed, and a random-effects model was applied. For outcomes with a large number of studies, funnel plots were used to assess publication bias. In the case of heterogeneity, a sensitivity analysis was conducted to explore potential sources. Additionally, subgroup analyses were performed to investigate factors that might influence the results. If outcomes could not be combined, descriptive methods were used to explore the findings. This approach ensured a thorough evaluation of the research findings and facilitated the identification and management of biases[49–51].

3. Results

3.1 Literature Search Results

A total of 611 articles were retrieved from the databases (99 from PubMed, 172 from the Cochrane Library, and 340 from Web of Science), along with 2 additional articles obtained through other sources. After removing 192 duplicate records, 421 articles remained. Of these, 186 review articles, conference abstracts, and theses were excluded, leaving 235 articles for further consideration. After screening the abstracts and topics, 145 articles that did not meet the inclusion criteria were excluded, resulting in a final pool of 90 articles. These articles were read in full, and based on the inclusion and exclusion criteria, 77 articles were further excluded, leaving 13 studies that met the inclusion criteria. These 13 studies were included in the qualitative analysis. Following an evaluation of the outcome measures, these

13 studies were incorporated into the quantitative analysis and subjected to a meta-analysis. The selection process is outlined in Fig 1.

3.2 Literature Quality Assessment

This study included 5 RCTs, which were assessed for risk of bias using the Cochrane Risk of Bias tool. The results revealed low risks in several critical areas: random sequence generation, completeness of outcome data, selective reporting, and other potential sources of bias. Four of the studies reported low risk in allocation concealment, while one study had an unknown risk. In terms of blinding, neither participants, researchers, nor assessors were classified as having a low risk of bias; only unknown or high risks were identified, suggesting that these factors might impact the validity of the findings. These results are illustrated in Fig2.

The remaining 8 studies were non-RCTs, evaluated using the MINORS scale. The average score across these studies was 10.75 (SD 1.39), with 5 of these studies categorized as high quality (scores ≥11). The analysis indicated comprehensive reporting on several key aspects, including clear study objectives, inclusion of consecutive patients, study design appropriateness, and prospective power calculations for sample size. However, the bias assessments for primary outcome measures were all rated 0 (not reported), and follow-up after the intervention was mostly rated 1 (reported but insufficient). These findings align with the results from the Cochrane Risk of Bias assessment. The assessment scores are displayed in Fig 3, where light green indicates 2 points (adequate reporting), green represents 1 point (inadequate reporting), and dark green represents 0 points (not reported).

3.3 Basic Characteristics of Included Studies

The 5 RCTs[52–56]included in the analysis involved a total of 349 participants who met the inclusion criteria, as detailed in Table 2. The remaining 8 studies[57–64]were non-RCTs (randomized crossover trials and within-group studies), involving 210 participants who met the inclusion criteria, as shown in Table 3.

The average age of participants across the included studies was 21 years, and all were healthy adolescents and young adults without any injuries or underlying medical conditions. The studies were conducted in the following countries: Japan (4 studies)[57,59,61,62], the UK (2 studies) [60,64], France (1 study)[58], the USA (1 study)[60], Canada (1 study)[52], Poland (1 study)[53], Germany (1 study)[54], China (1 study)[55], and Wales (1 study) [56]. Seven studies involved interventions lasting less than 30 minutes[52–55,57,59,64], while six studies had interventions lasting 30 minutes or more[56,58,60–63]. Among the HIIE interventions, 3 studies[57,63,64] used running, 8 studies[52,53,55,58–62] used cycling, and the remaining 2 studies[54,56] combined different exercise modalities. In the RCTs, the control group consisted of either no exercise with rest or maintenance of normal lifestyle habits. The primary outcome measures were reaction time (RT) and accuracy in the Stroop Task.

3.4 Meta-Analysis Results

3.4.1 Stroop Task Reaction Time in Single-Arm Studies

A total of 13 studies were included[52–64], the analysis includes 5 RCT studies and 8 single-arm studies. We incorporated the pre-test and post-test data from the intervention group of the RCT studies into the single-arm studies for the meta-analysis. This means that there are 13 data sources for the single-arm studies in this research. with 307 adolescent participants. A random-effects model was used for analysis ($P < 0.00001$, $I^2 = 88\%$), and SMD was employed due to inconsistencies in unit measurement. The results (see Fig4A) showed a significant difference in Stroop Task reaction times between pre-test and post-test in the experimental group (WMD = -1.47, 95% CI -1.98 to -0.97, $P < 0.00001$). As indicated by the funnel plot (See Fig 4B), most studies were concentrated around the center, but a few deviated, suggesting substantial heterogeneity. Sensitivity analysis was conducted to identify the source of heterogeneity[65–67]. After excluding four studies[53,57,59,61], the statistical results remained consistent, and a fixed-effects model was applied ($P = 0.84$, $I^2 = 0\%$), with all

studies included in the funnel plot, eliminating the heterogeneity (see Fig5). A descriptive analysis of the original studies indicated that, in Burin's study [57], HIIE was combined with virtual reality (VR) technology, which altered the training experience compared to real-life interventions, potentially leading to biased results. In Hashimoto's[59]cycling intervention study, participants adopted a semi-recumbent position with a 40° upper body tilt. During rest, their legs were stretched out on the bed, while during exercise, their legs were fixed to the bicycle pedals. This posture restriction could have caused discomfort, resulting in discrepancies compared to other studies. In Tsukamoto's[61]study, participants rested for 7 minutes in a seated position after completing the Stroop Task, prior to starting the HIIE test. This additional rest period might have contributed to biased results. Kujach's[53]study featured a relatively short intervention duration of only 12.5 minutes, insufficient to produce the expected effects of HIIE. In summary, compared to pre- and post-intervention data, HIIE effectively reduced Stroop Task reaction time and improved adolescents and young adults executive function.

3.4.2 Subgroup Analysis of Stroop Task Reaction Time in Single-Arm Studies

A subgroup analysis was performed on the 13 included studies based on key characteristics to identify potential influencing factors. The first factor considered was the duration of the single intervention. Among the 13 studies, 7 had an intervention duration of less than 30 minutes[52–55,57,59,64], while the remaining 6 had an intervention duration of 30 minutes or more [56,58,60–63]. Thus, the studies were divided into two subgroups for analysis. Based on the previous sensitivity analysis, four studies with substantial heterogeneity were excluded. The results, shown in Fig6A, revealed that in the subgroup with an intervention duration of less than 30 minutes, four studies[52,54,55,64] showed significant results ($P < 0.00001$) with no heterogeneity ($P = 0.85$, $I^2 = 0\%$). Similarly, in the subgroup with an intervention duration of 30 minutes or more, five studies[56,58,60,62,63]demonstrated significant results ($P < 0.00001$) with no heterogeneity

(P = 0.43, I^2 = 0%). The funnel plot (See Fig 6B) confirmed that studies in both subgroups were evenly distributed within the funnel area, with no signs of heterogeneity. In the subgroup of <30 minutes, three studies[53,57,59] were excluded. In the study by Kujach[53], each sprint lasted 30 seconds; in the study by Burin[57], each running session lasted 30 seconds, with relatively short high-intensity exercise durations. In the study by Hashimoto[59], there was a 60-minute rest interval between the two bouts of HIIE, and the prolonged rest period led to a decline in exercise effectiveness. Therefore, compared to short-duration HIIE, interventions with a duration of ≥30 minutes may be more effective.

The next factor considered was the type of intervention. In the 13 studies, 3 used running[57,63,64], 8 used cycling[52,53,55,58–62], and 2 used a combination of different exercises[54,56]. The studies were thus divided into three subgroups for analysis. Excluding the four studies with high heterogeneity, the results, shown in Fig 7A, revealed the following: In the running subgroup, two studies[63,64]showed significant results (P < 0.00001) with minimal heterogeneity (P = 0.32, I^2 = 12%). In the cycling subgroup, five studies[52,55,58,60,62] showed significant results (P < 0.00001) with no heterogeneity (P = 0.53, I^2 = 0%). In the combined exercise subgroup, two studies[54,56]showed significant results (P = 0.002) with no heterogeneity (P = 0.83, I^2 = 0%). The funnel plot (See Fig 7B) indicated that studies in all three subgroups were evenly distributed within the funnel area, with no heterogeneity present. In all three subgroups, the results were significant and exhibited no heterogeneity. The cycling subgroup contained the largest number of studies, suggesting that most HIIE interventions prioritize cycling, which produces stable and favorable results. Other interventions, such as running and combined exercises, also yielded significant effects and could be considered for further studies.

3.4.3 Stroop Task Accuracy in Single-Arm Studies

A total of 8 studies were included[55,58–64], with 181 adolescent participants. A random-effects model was used for analysis (P < 0.00001, I^2 = 91%), and the results (see Fig

8A) revealed a significant difference in Stroop Task accuracy between pre-test and post-test in the experimental group (WMD = -1.14, 95% CI -1.76 to -0.52, P = 0.0003). The funnel plot (See Fig 8B) indicated that most studies were concentrated around the center, but some deviated, pointing to strong heterogeneity. Sensitivity analysis was conducted to explore the source of this heterogeneity. After excluding four studies[55,62–64], heterogeneity was reduced, and a fixed-effects model was applied (P = 0.2, I^2 = 33%), with all studies included in the funnel plot (See Fig 9B), though the studies still showed some deviation (see Fig 9A). A descriptive review of the original studies suggested that in three studies [55,63,64], the cause of heterogeneity was likely due to short intervention durations, as interventions lasting less than 30 minutes were insufficient to produce effects. In Tsukamoto's[62]study, participants rested for 20 minutes after completing the Stroop Task to eliminate the influence of the pre-and post-exercise time intervals. This extra rest period might have caused data bias. The results indicate that compared to pre- and post-intervention data, HIIE interventions reduced Stroop Task accuracy, leading to errors in judgment during the task.

3.4.4 Stroop Task Reaction Time in RCT Studies

A total of 5 studies were included[52–56], with 175 adolescent participants. A random-effects model was used for analysis (P = 0.0008, I^2 = 79%), and the results (see Fig 10A) showed no significant difference in Stroop Task reaction times between the intervention and control groups, with significant heterogeneity (WMD = -0.17, 95% CI -0.86 to 0.51, P = 0.62). The studies were also dispersed in the funnel plot (See Fig 10 B). Given the small number of studies and the lack of statistical differences in most, sensitivity analysis was not conducted. The results suggest that HIIE intervention did not significantly reduce Stroop Task reaction time compared to the control group.

4. Discussion

This study examines the effects of HIIE on performance in the Stroop Task. The results indicate that HIIE may reduce reaction times in the Stroop Task, with a potentially

stronger effect when the exercise duration is ≥ 30 minutes. However, findings from RCTs did not reveal a significant reduction in Stroop Task reaction times due to HIIE. Additionally, the study found that HIIE intervention did not significantly enhance accuracy in the Stroop Task. Regarding intervention methods, cycling remains the preferred modality for HIIE interventions, although other forms of exercise have also shown some positive effects.

4.1 The Stroop Task and Cognitive Function

The Stroop Test is a well-established psychological task used to assess cognitive interference, attention control, and inhibitory control abilities[68]. Introduced by psychologist John Ridley Stroop in 1935, the test aims to examine an individual's response times and cognitive load when confronted with conflicting information[69]. A standard Stroop test includes three task conditions: the congruent condition (where the meaning of the words aligns with the font color), the incongruent condition (where the meaning of the words conflicts with the font color), and the neutral condition (where words are unrelated to color and are replaced by neutral terms). The congruent condition, devoid of cognitive conflict, primarily reflects the participant's basic attention control and information processing speed in an interference-free context. The incongruent condition requires participants to inhibit automatic word meaning responses and instead focus on color recognition. This condition reflects the participant's ability to manage cognitive conflict by regulating behavior and suppressing automatic responses. The neutral condition, in which words and font colors are unrelated, serves to assess an individual's ability to maintain attention in the absence of cognitive conflict[70–73]. Collectively, these three conditions provide insights into cognitive flexibility.

4.2 Variations in Reaction Time and Accuracy Across Stroop Task Conditions

This study primarily analyzes reaction time and accuracy in the Stroop Task. Reaction time is an indicator of a participant's responsiveness, as well as their information processing speed and capacity. Accuracy, on the other hand, reflects cognitive control, including

attention regulation and focus. Notably, there are differences in reaction time and accuracy across the three Stroop task conditions. In the congruent condition, where the meaning of the word matches the font color, reaction times are typically shorter due to the absence of cognitive conflict, enabling participants to quickly access the correct information, which results in higher accuracy. In the incongruent condition, where word meanings and font colors conflict, participants must inhibit the automatic response to the word's meaning and focus on identifying the color. This additional cognitive load leads to longer reaction times, and participants may struggle to suppress automatic responses, resulting in errors and lower accuracy. In the neutral condition, where words and font colors are unrelated, reaction times are usually shorter than in the incongruent condition but tend to be longer than in the congruent condition. Given the lack of cognitive conflict, accuracy in the neutral condition is generally higher, approaching the level observed in the congruent condition[74].

4.3 The Maximum Benefits of HIIE Duration

In the previous results, the meta-analysis found that exercise durations of ≥30 minutes lead to faster reaction times compared to shorter durations. Although the reaction speed improves, accuracy decreases, highlighting the speed-accuracy trade-off. It cannot be assumed that HIIE exercises lasting ≥30 minutes are necessarily more beneficial for improving executive function in adolescents and young adults. Additionally, HIIE requires careful consideration of both high-intensity exercise and rest period design. Typically, high-intensity exercise lasts between 30 seconds and 4 minutes, reaching 80%-95% of the maximum heart rate, while rest periods range from 10 seconds to 4 minutes, during which the heart rate drops to 40%-50%. Typically, 4-10 cycles are performed. However, the specific duration of exercise, rest intervals, and number of cycles can vary across different HIIE designs. For instance, the Tabata method, developed by Japanese scientist Dr. Izumi Tabata, features extremely short high-intensity exercise periods and rest times (30 seconds of very high-intensity exercise followed by 10 seconds of complete rest, repeated for 8 cycles). This method aims to

significantly improve cardiovascular and muscular endurance in a short period. In contrast, long-duration HIIE involves longer high-intensity exercise periods, along with longer rest intervals (e.g., 4 minutes of high-intensity exercise followed by 3 minutes of rest, repeated for 4-6 cycles), focusing on improving aerobic endurance, fat metabolism, and overall physical fitness[74–76].

In summary, whether long-duration HIIE is more effective than short-duration HIIE in improving cognitive function requires further exploration and additional studies. In everyday exercise routines, HIIE is generally recommended to last around 20-30 minutes, taking into account both the high-intensity exercise duration and the rest periods. If the HIIE duration is too short, it may not produce optimal effects, whereas excessive duration or overly intense design may increase physical strain and injury risks. Therefore, appropriately designed HIIE is the most recommended approach. Furthermore, the design of HIIE is closely related to individual physical factors. For adolescents and young adults with good physical fitness and cardiovascular function, progressively increasing the high-intensity exercise duration or shortening rest periods based on individual conditions can yield better exercise benefits. This approach can not only improve cardiovascular function and enhance strength and endurance but also improve information processing ability and attention control[77–79].

4.4 Differences in HIIE Intervention Across Different Study Designs

The studies included in this research did not impose restrictions on study type, and both RCTs and randomized crossover trials were included. The outcome measure of Stroop Task RT was analyzed separately in single-arm studies and RCTs. In single-arm studies, data from pre- and post-intervention were compared, while in RCTs, data from the intervention group and control group were compared. The results showed a significant reduction in Stroop Task reaction time in single-arm studies, while no significant differences were observed in RCTs. Single-arm studies are typically exploratory or in the early stages of intervention research. Without a control group, any observed changes in single-arm studies cannot be

definitively attributed to the intervention itself, as external factors (e.g., time effects, participant expectations) may also play a role. In contrast, RCTs provide higher-quality evidence by using a control group for comparison, and their results are considered more robust because they more directly attribute changes to the intervention, minimizing the influence of other variables. Therefore, RCTs are generally regarded as more reliable and provide stronger evidence. Many of the studies included in this research were randomized crossover trials, in which the same group underwent different interventions. This design could lead to cross-interference between interventions, resulting in cumulative participant load and potentially affecting the outcomes. Therefore, additional RCT studies are needed to further validate these findings.

4.5 The Speed-Accuracy Trade-off in HIIE Intervention

The results of this study indicate that HIIE improves reaction times in cognitive tasks among adolescents and young adults, but accuracy does not improve. This phenomenon can be explained by the concept of the speed-accuracy trade-off (SAT). SAT is a concept in cognitive psychology that refers to the need to balance fast responses with accurate ones when performing cognitive tasks[80]. In this study, participants may have prioritized faster response times following HIIE intervention, which, to some extent, sacrificed accuracy. From a theoretical perspective, when individuals attempt to speed up their responses, they may reduce the depth of processing task details, leading to an increase in error rates. Conversely, when individuals focus on improving accuracy, they may take longer to respond to perform more detailed cognitive processing[81,82]. In some cases, improving reaction speed may be beneficial, especially in situations that require quick decision-making. However, maintaining accuracy is equally important, as it directly influences the effectiveness of information processing. Future research should further explore how to enhance response speed while maintaining accuracy, in order to achieve a comprehensive improvement in cognitive function in adolescents and young adults.

4.6 Study Limitations

This study has several limitations: ① The full-text access for some articles was incomplete, and certain articles were difficult to retrieve directly from browsers. Attempts were made to contact authors to obtain the complete articles, which may have resulted in the exclusion of some studies; ② The included studies did not report on the blinding of researchers or participants, allocation concealment was vaguely described, and the reasons for dropout and loss to follow-up were not clearly stated, which led to a lower quality assessment of the studies. To improve the credibility of the analysis, future research should include high-quality studies with larger sample sizes and adherence to clinical research guidelines; ③ The outcome measures used to assess cognitive and executive functions were limited, and a broader range of objective measures should be employed in future evaluations; ④ The number of RCTs included was relatively small, leading to potential bias in the analysis; ⑤ The outcome measures primarily reflect adolescents and young adults executive function and cognitive flexibility, but other cognitive characteristics should also be explored.

5. Conclusion

This study found that HIIE can reduce reaction times in the Stroop Task, and that exercise durations of ≥30 minutes may be more effective. However, the results from RCTs did not show significant reductions in Stroop Task reaction times with HIIE. Currently, cycling is the preferred form of HIIE intervention, though other methods have also shown significant effects. Furthermore, HIIE intervention did not significantly improve accuracy in the Stroop Task. Therefore, future studies should include larger sample sizes and more rigorously designed RCTs to further investigate the effects of HIIE on cognitive function in adolescents and young adults.

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Table 1. PICOS strategy

PICOS	Selection Criteria
Population	Healthy adolescents and young adults and young adults aged 12-30 years with no injuries or diseases
Intervention	including high-intensity interval exercise (HIIE); High-Intensity Interval Aerobic Training (HIAT); High-Intensity Interval Resistance Training (HIIRT); High-Intensity Interval Functional Training (HIIFT), etc., as acute interventions.
Comparison	No intervention content; conventional training; daily activities; rest, etc.
Outcome	The Stroop Task includes Reaction Time (RT) and Accuracy.
Study design	single-arm studies; Randomized Controlled Trials (RCT); Randomized Crossover Trials, etc.

Note：P：Population；I：Intervention；C：Comparison；O：Outcome；S：Study design

Table 2. Basic Characteristics of Included RCT Studies

Study	Country	Design	Population	Group	Duration	Intervention	Comparison	Measures
Brown[52]（2018）	Canada	RCT	177 university students (age: ±20 years)	HIIE：22 CG：20	20min	During the high-intensity interval, participants pedal at 70% of their peak power output with a cadence of 90–120 RPM for 1 minute (Wpeak), alternating with low-intensity intervals where they pedal at 12.5% of their peak power output with a cadence of 60–90 RPM for 1 minute (Wpeak).	Participants in the no-exercise condition sat on the cycle ergometer for 25 minutes, with the ergometer set in a way that prevented them from pedaling.	a
Kujach[53]（2020）	Poland	RCT	36 healthy young adults (mean age: 21 years)	SIE：20 CG：16	12.5min	Warm-up for 5 minutes, followed by intermittent exercise consisting of 6 sets of 30-second "all-out" sprint cycling, then a 4.5-minute rest on the cycle ergometer.	No exercise intervention, resting in a resting state.	a
Wilke[54]（2020）	Germany	RCT	35 sports science students (age: 26.7 ± 3.6 years)	HIT：12 CG：12	15min	The training includes 15 functional full-body exercises performed in a circuit, with 20 seconds of full effort followed by 10 seconds of rest, resulting in 30 exercise cycles per session.	No participation in exercise, required to read for 15 minutes.	a
Hu[55]（2021）	China	RCT	32 healthy young women (age: 18-30 years)	HIIE：16 CG：16	20min	The training plan alternates between 3 minutes at 50% HRR and 2 minutes at 90% HRR for 4 rounds.	Maintaining a normal lifestyle without training.	a,b
De Diego-Moreno[56]（2022）	Wales	RCT	69 young adults (age: 21.01 ± 2.79 years)	HIT：27 CG：14	30min	The HIFT group underwent a 30-minute circuit-based fitness training program consisting of 6 exercises (squats, push-ups, lunges, dips, box jumps, planks), with 10 repetitions of each exercise continuously, followed by a 2-minute rest after completing one round of the 6 exercises.	No training protocol was provided.	a

Note: RCT: Randomized Controlled Trial; HIIE: high-intensity interval exercise; CG: Control Group; HIFT: High-Intensity Functional Training; SIE: Short-Term HIIE; RPM: Revolutions Per Minute; Wpeak: Peak Power Output; HRR: Heart Rate Reserve; Stroop Task Reaction Time [a]; Stroop Task Accuracy [b].

Table 3. Basic Characteristics of Included Non-RCT Studies

Study	Country	Design	Population	Duration	Intervention	Measures
Burin[57]（2020）	Japan	Randomized Crossover Trial	45 healthy young adults (Age: 23.7 ± 4.5)	8min	Participants observed a virtual body alternating between 30 seconds of running and 30 seconds of slow walking, then performed high-intensity exercise (HIE) training by running and walking according to the virtual body's speed.	a
Dupuy[58]（2018）	France	Randomized Crossover	20 moderately trained young adults (Age:	60min	A series of six 3-minute cycling bouts at 95% HIIE, interspersed with 3-minute passive recovery periods.	a,b

		Trial	28.0 ± 4.8)			
Hashimoto[59]（2018）	Japan	Randomized Crossover Trial	14 healthy young adults (Mean age: 24.61)	28min	The maximal workload (Wmax) was determined before the experiment. Before HIIE, a 5-minute warm-up at 50–60% Wmax was conducted. The experiment consisted of four 4-minute exercise bouts at 80–90% Wmax, with four 3-minute exercise bouts at 50–60% Wmax in between.	a,b
Miller[60]（2018）	US	Within-group Trial	25 young adults (Age: 23 ± 2.79)	30min	Participants were required to complete a 5-minute warm-up on a Watt bike before starting the HIIE intervention. They were informed of the target HR range (80–85% HRmax) and instructed to maintain their HR within this range during exercise.	a,b
Tsukamoto[61]（2015）	Japan	Randomized Crossover Trial	12 healthy young individuals (Age: 22.9 ± 0.4)	33min	The HIIE protocol initially involved a 5-minute session at 60% of peak VO_2, followed by four 4-minute bouts at 90% of peak VO_2, interspersed with 3-minute active recovery periods at 60% of peak VO_2.	a,b
Tsukamoto[62]（2016）	Japan	Randomized Crossover Trial	12 healthy young adults (Age: 23.2 ± 0.5)	80min	Participants performed exercise sessions at 30% VO_2peak for 20 minutes, 60% VO_2peak for 20 minutes, and 30% VO_2peak for 40 minutes, respectively.	a,b
Hatch[63]（2021）	UK	Randomized Crossover Trial	38 adolescents and young adults (Mean age: 12.4)	30min/60min	The protocol included three 20-meter shuttle runs at walking pace, followed by a 15-meter sprint with rest (total duration: 8 s). Additionally, three 20-meter shuttle runs were performed at 85% of VO_2peak, three at 55% of VO_2peak, and the sequence was repeated eight times.	a,b
Cooper[64]（2015）	UK	Randomized Crossover Trial	44 adolescents and young adults (Age: 12.6 ± 0.6)	10min	Participants performed high-intensity interval running, consisting of 10-second sprints followed by 50 seconds of active recovery (walking), repeated 10 times.	a,b

Note: HIIE: high-intensity interval exercise; Wmax: Maximal Workload; HR: Heart Rate; HRmax: Maximum Heart Rate; VO_2: Oxygen Uptake; VO_2peak: Peak Oxygen Uptake; Stroop Task Reaction Time [a]; Stroop Task Accuracy [b]

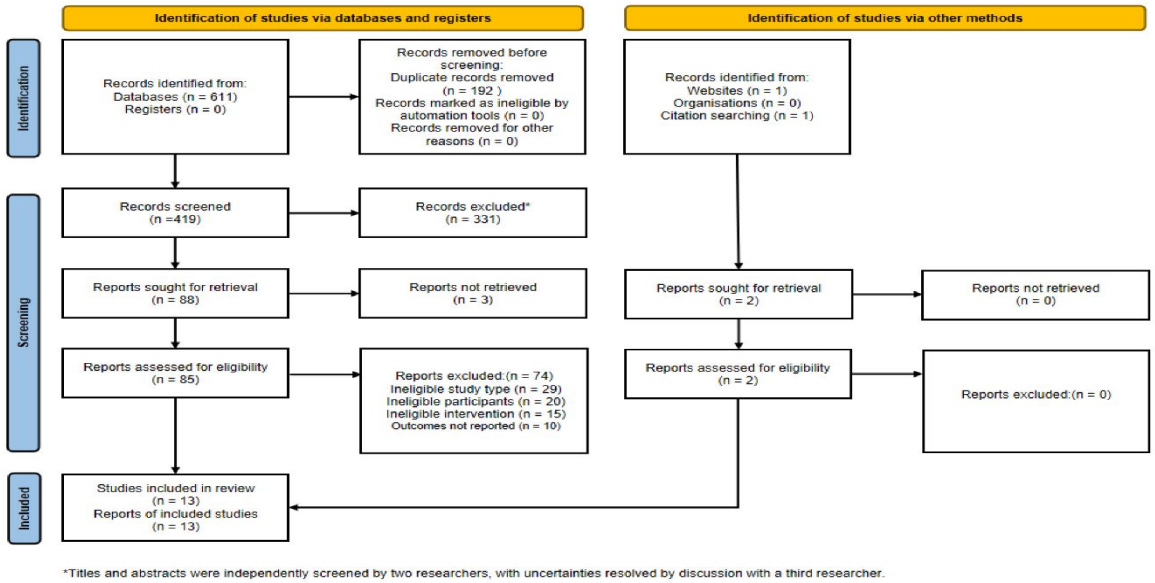


Fig. 1. Literature Screening Flowchart

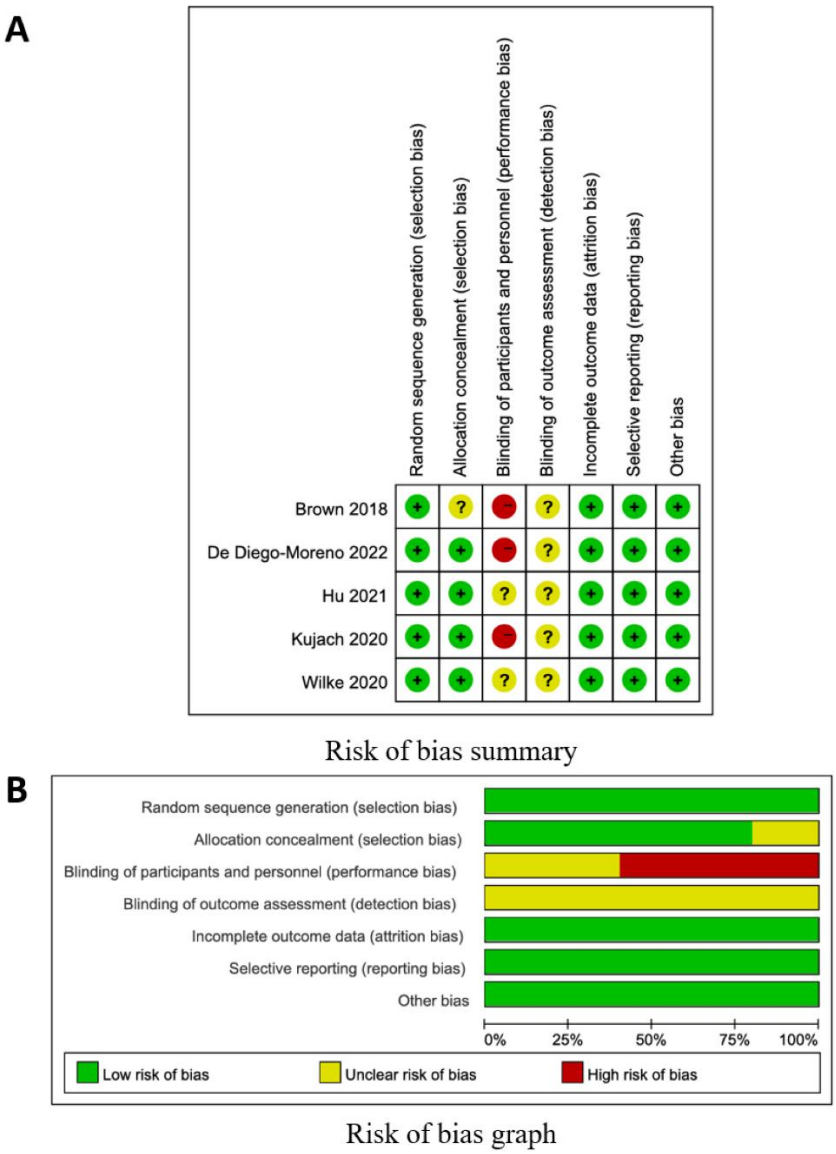
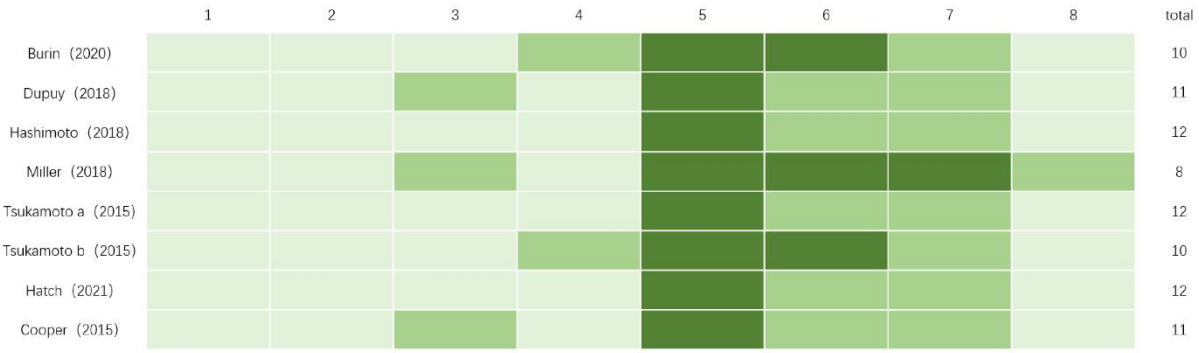


Fig. 2. Cochrane Risk of Bias Assessment (A. Risk of bias for individual studies; B. Risk of bias for each item)



Note: 1: A clearly stated aim; 2: Inclusion of consecutive patients; 3: Prospective collection of data; 4: Endpoints appropriate to the objective of the study; 5: Unbiased assessment of the study endpoint; 6: Follow-up period applicable to the aim of the study; 7: Loss to follow up less than 5%; 8: Prospective calculation of the study size.

Fig. 3. MINORS Evaluation Scale

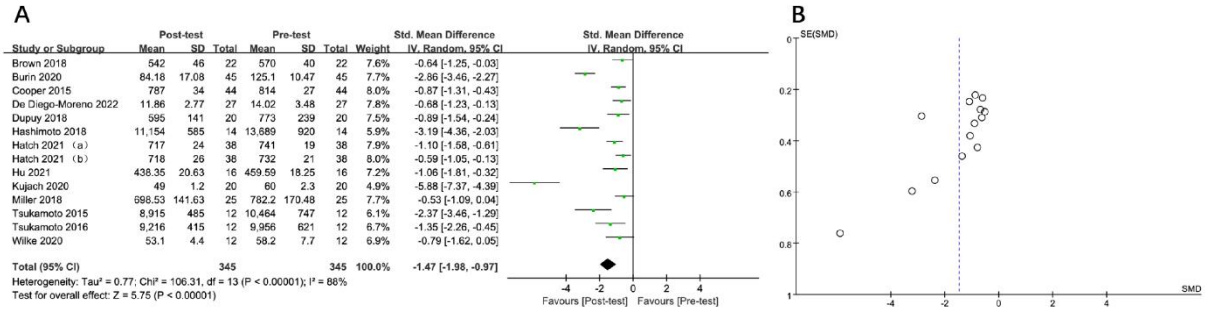


Fig. 4. Response Time for the Stroop Task in Single-Arm Studies (A. Forest plot; B. Funnel plot)

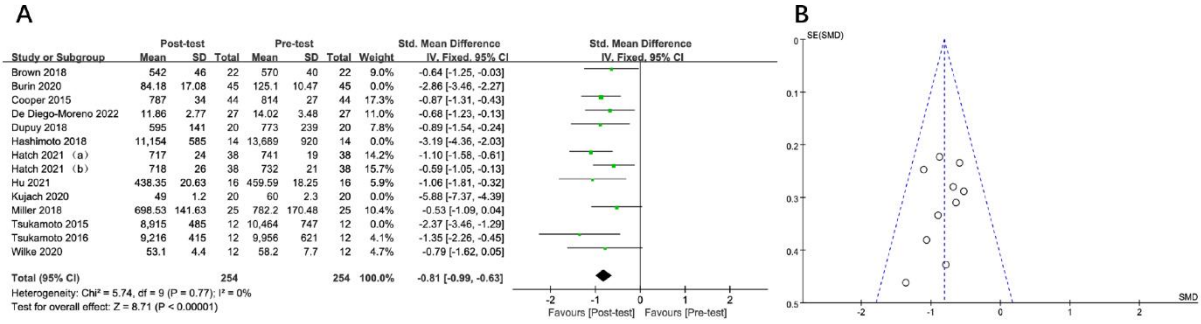


Fig. 5. Sensitivity Analysis of Stroop Task Response Time in Single-Arm Studies (A. Forest plot; B. Funnel plot)

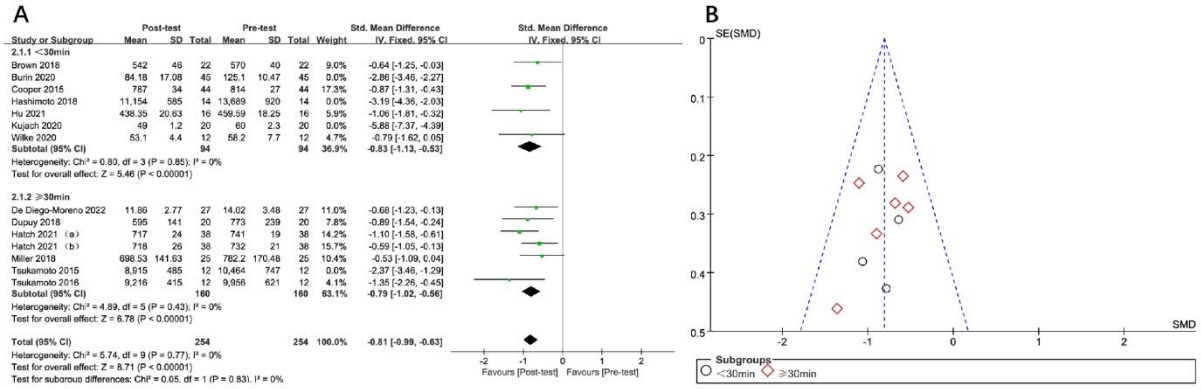


Fig. 6. Subgroup Analysis of Stroop Task Response Time in Single-Arm Studies(Intervention Duration) (A. Forest plot; B. Funnel plot)

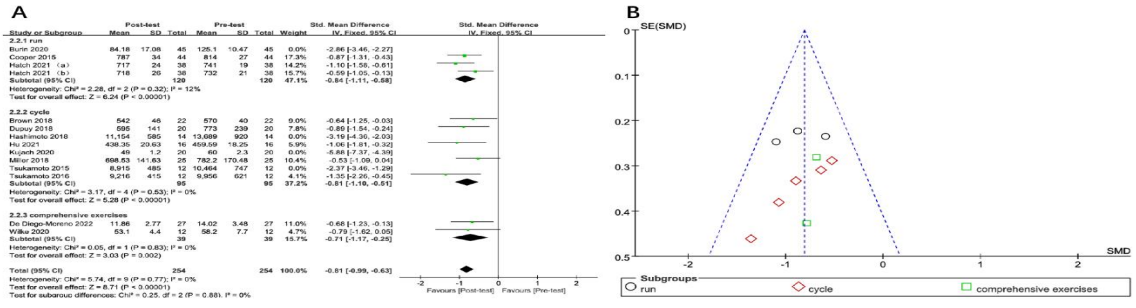


Fig. 7. Subgroup Analysis of Stroop Task Response Time in Single-Arm Studies (Intervention Type) (A. Forest plot; B. Funnel plot)

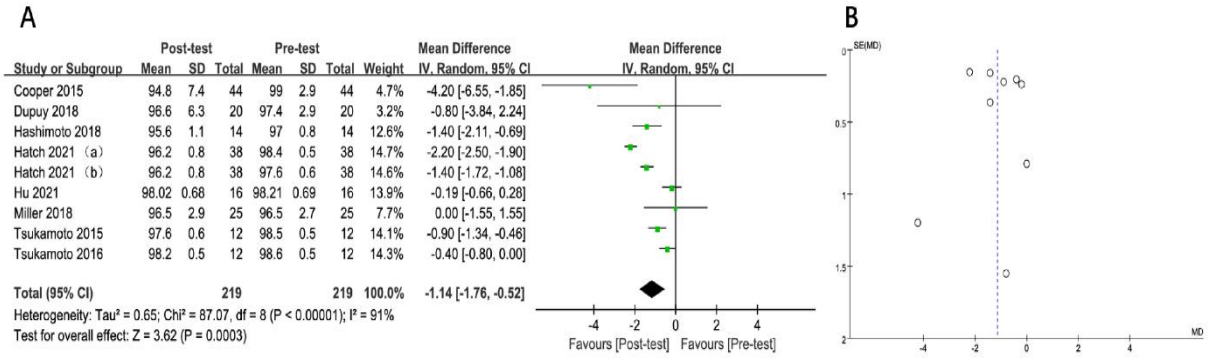


Fig. 8. Accuracy of the Stroop Task in Single-Arm Studies (A. Forest plot; B. Funnel plot)

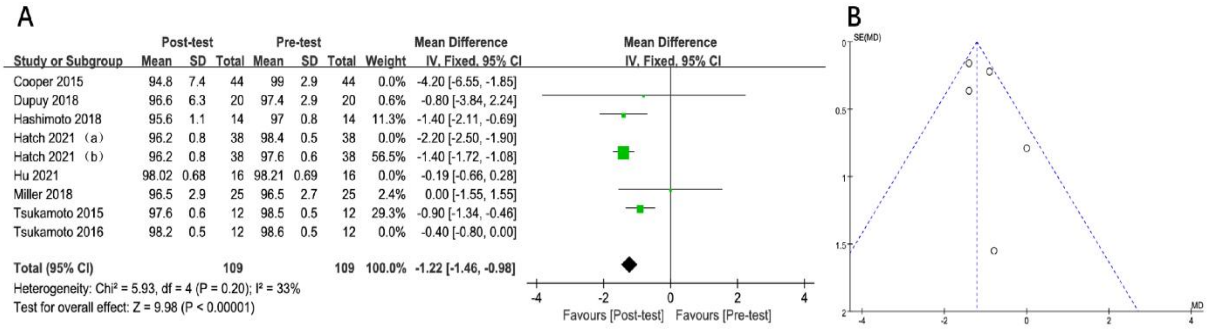


Fig. 9. Sensitivity Analysis of Stroop Task Accuracy in Single-Arm Studies (A. Forest plot; B. Funnel plot)

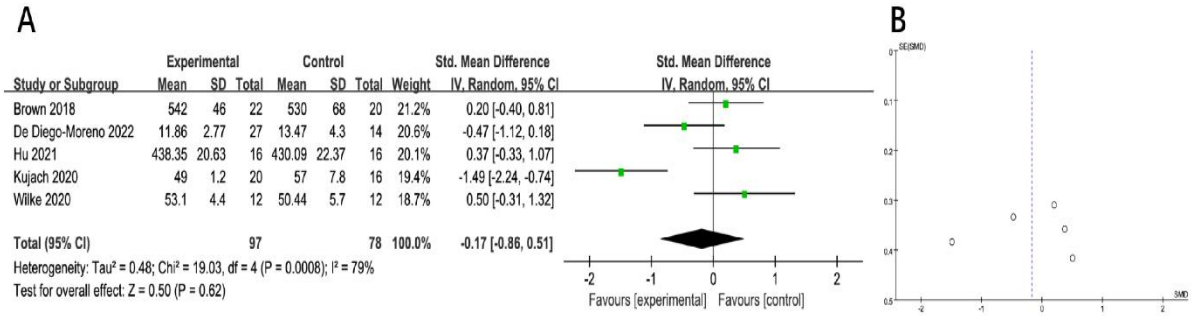


Fig. 10. Response Time for the Stroop Task in RCT Studies (A. Forest plot; B. Funnel plot)