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OBM Integrative and Complementary Medicine

Review

Does a Single Bout of Aerobic Exercise Improve Set Shifting in Healthy Young Adults? A Systematic Review and Meta-Analysis

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Academic Editor: Paul D. Loprinzi

Special Issue: Research of Exercise and Cognitive Function

OBM Integrative and Complementary Medicine
2019, volume 4, issue 3
doi:10.21926/obm.icm.1903052

Received: April 24, 2019
Accepted: August 19, 2019
Published: August 28, 2019

Abstract

This systematic review and meta-analysis investigated whether acute aerobic exercise improves subsequent set shifting performance in healthy young individuals. Potential moderation of studies' methodological quality and exercise intensity, as well as the presence of small-study effect was also examined. Studies were identified using electronic databases Medline, PsycINFO, and SPORTDiscus, as well as references of recent meta-analyses and references of included studies. In total, 12 studies were included into qualitative synthesis. Eleven studies that contained data from 1,189 healthy young individuals were eligible for inclusion in the meta-analysis. The effect size of each trial was calculated as bias corrected Hedges' g standardized mean difference. A random-effects model was used to pool outcomes across studies. Sensitivity analysis was conducted to investigate influence of outliers and of studies with mixtures of aerobic and anaerobic exercise. Meta-regression and subgroup analyses were used to examine moderation. A small to moderate significant beneficial effect of acute aerobic exercise on subsequent set shifting performance compared to control (Hedges' g = -.26, 95 % CI -.49 to -.02, p = .03) with large true heterogeneity was revealed (I^2 = 70.9%, Q=44.61, p<.0001). Results became homogenous when two outliers were removed from the analysis (I^2=0%, Q=6.52, p=.84) while summary effect size estimate stayed comparable (Hedges' g = -.23, 95 % CI -.38 to -.-.08, p = .003). Studies' methodological quality and exercise intensity did not modify effect size estimates. There was no indication of small-study effect detected. This review shows that even healthy young adults, who are at the peak of their physiological and cognitive capacities, show improved set shifting performance following a single bout of aerobic exercise. The results indicate that these effects are not due to methodological shortcomings, exercise intensity, or small-study effect. The results indirectly support the conclusion that these effects are a result of physiological and/or psychological adaptations to the exercise.

Keywords
Exercise; physical activity; cognition; cognitive flexibility; Trail Making Test; set shifting

1. Introduction

The term "executive functions" stands for processes which are necessary to control or regulate other cognitive processes in the service of goal-directed behavior [1]. There is still an ongoing debate as to what cognitive processes should be subordinated under the umbrella term executive functions [2]. Modern theoretical perspectives suggest inhibition, working memory, and cognitive flexibility as core executive functions [3].

Acute aerobic exercise increases prefrontal oxygenation [4]. Moreover, acute aerobic exercise is associated with an increase in cerebral blood flow [5], and metabolic status of cerebral neurons [6, 7]. Therefore, it was assumed that acute aerobic exercise has the potential to improve subsequent executive function performance.

Evidence indicates that the effects of acute aerobic exercise on distinct executive function subdomains are differential [8]. Among the most frequently studied outcomes is cognitive set shifting. Cognitive set shifting is a subdomain of cognitive flexibility [9]. It describes the ability to shift attention from one attribute of a stimulus to another, in order to execute goal-directed behavior [10].

Several studies conducted with psychiatric patients [11, 12], older healthy individuals [13, 14], and children, [12, 15] report improvements in set shifting performance following a single bout of aerobic exercise. However, it was recently questioned if these beneficial effects of acute aerobic exercise on subsequent set shifting performance can also be found in samples that comprise solely of healthy young individuals [16]. During young adulthood, individuals typically reach their peak cognitive set shifting performance [17]. It is questionable to what extent healthy young adults, who are at the peak of their cognitive capacities, have potential left for exercise induced cognitive improvement [18, 19]. There is evidence which shows that individuals with lower baseline cognitive performance benefit most from acute aerobic exercise [20, 21].

Studies that investigated the effect of acute aerobic exercise on subsequent set shifting performance in healthy young adults show inconsistent results. Some studies report significant set shifting facilitation following a single bout of aerobic exercise [22, 23]. Other studies show no benefits or even a decline in set shifting performance after acute aerobic exercise [24, 25]. A recent meta-analysis investigated the effect of acute aerobic exercise on subsequent executive function dependent test performances in healthy young adults. A beneficial effect was shown [26]. Meta-analyses that examine the after-effect of acute aerobic exercise specifically on executive function subdomain set shifting in healthy young adults are lacking until today.

It was argued that the empiric results, which show facilitation of set shifting in healthy young adults after acute aerobic exercise, are the result of bias due to methodological shortcomings and not a result of physiological and/or psychological adaptations to the exercise [27]. It was also discussed if small-study effect might play a role in research on the after-effect of acute aerobic exercise on set shifting performance in healthy young adults [26, 28]. The term "small-study effect" describes the phenomenon that smaller studies sometimes show different, often larger, treatment effects than larger studies [29]. One reason for this is publication bias. Publication bias results from selective publication of studies, which is based on the direction and magnitude of the empirical results [30].

It was also discussed whether the intensity of the preceding acute aerobic exercise session moderates its effects on subsequent set shifting in healthy young adults [16]. The magnitude of most physiological adaptations to exercise, which might underlie cognitive benefits of acute aerobic exercise, are directly associated with the exercise's intensity [5-7].

In this systematic review and meta-analysis, we investigated the effect of acute aerobic exercise on subsequent set shifting performance in healthy young adults. To examine potential moderation of studies' methodological quality, meta-regression was used. To investigate the presence of small-study effect, Funnel plots and Egger's tests were conducted. To examine potential moderation of exercise intensity, subgroup analyses were employed.

2. Materials and Methods

Reporting is in accordance with "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) guidelines [31, 32].

2.1 Study Selection

Eligible studies for this review were peer-reviewed and published in the English language. No limits were applied concerning the year of publication. We included studies that:

- (1) examined healthy young individuals (18-35 years of age)
- (2) applied a single bout of aerobic exercise of 10 to 60 minutes duration and of light to vigorous intensity (see details below)
- (3) compared the effects of acute aerobic exercise with a control condition, not reaching the threshold for light intensity exercise as defined below
- (4) applied neuropsychological tests measuring set shifting performance (see details below) and administered these tests immediately to 60 minutes after exercise cessation
- (5) used either a randomized controlled crossover or a randomized controlled trial design.

Aerobic exercise was understood as defined by the American College of Sports Medicine. They define aerobic exercise as any activity that uses large muscle groups, can be maintained continuously, and is rhythmic in nature [33]. The definitions of light, moderate, and vigorous exercise were operationalized according to the guidelines by Norton and colleagues [34]. Exercise was defined as light if the article reported a rating of perceived exertion between 8-10 on the Borg scale, a heart rate between 40% to 55% of the maximum heart rate, a heart rate between 20% to 40% of the heart rate reserve, or an oxygen uptake between 20% to 40% of the maximum oxygen uptake. Exercise was defined as moderate if the article reported a rating of perceived exertion between 11-13 on the Borg Scale, a heart rate between 56% to 70% of the maximum heart rate, a heart rate between 41% to 60% of the heart rate reserve, or an oxygen uptake between 41% to 60% of the maximum oxygen uptake. Exercise was defined as vigorous if the article reported a rating of perceived exertion between 14-16 on the Borg Scale, a heart rate between 71% to 90% of the maximum heart rate, a heart rate between 61% to 85% of the heart rate reserve, or an oxygen uptake between 60% to 85% of maximum oxygen uptake.

Neuropsychological tests that measure set shifting performance use the same principle. In order to solve the task, the participant must switch his attention from one attribute of the goal stimulus to another. This means that the participant must switch the cognitive set [35]. The increase in time and/or accuracy in the set shifting condition compared to a simple information processing condition (no switching of cognitive set necessary) is often referred to as “switch cost.” Among the most popular neuropsychological procedures to measure set shifting are the Trail Making Test and the Wisconsin Card Sorting Test. More detailed explanations of these procedures can be found via Basso and colleagues [36] and Slusher and colleagues [23].

Studies were excluded if they:

- (1) examined ill individuals or animals
- (2) applied acute resistance/strength exercise or repeated exercise sessions
- (3) compared two acute aerobic exercise treatments with each other both leading to a significant increase in heart rate
- (4) conducted cognitive testing only during exercise
- (5) neither reported adequate data for meta-analysis nor answered to data request via email.

2.2 Search Strategy

Electronic database search was conducted via EBSCO Host using Medline, PsycINFO, and SPORTDiscus (last updated on 25th of January, 2019). The following search algorithm was used to identify relevant studies:

(exercis [Title] OR sport* [Title] OR "physical activity" [Title] OR "physical exertion" [Title] OR running [Title] OR jogging [Title] OR walking [Title] OR bicycling [Title]) AND (cogniti* [Title] OR "executive function*" [Title] OR “cognitive flexibility” [Title] OR “set shifting” [Title] OR “reaction time” [Title] OR attention [Title] OR "Trail Making” [Title] OR “Wisconsin Card Sorting” [Title]).*

In addition to electronic database search, references of recent systematic reviews on the effect of acute exercise on subsequent cognitive performances [26, 28, 37], as well as the references of all included articles, were screened for further eligible records. Duplicates were removed. Titles and abstracts were screened. If a title and/or an abstract indicated potential eligibility for inclusion in this review or if the abstract was missing, the full text article was read. Studies were included if fulfilling the above defined selection criteria were fulfilled. Two members of the review team (M.O.

and S.S.) independently conducted the literature search. Any disagreements were resolved by discussion.

2.3 Outcome Measures and Data Extraction

The number of participants in each experimental group and the means and standard deviations (or standard errors) of time-dependent and accuracy measures of set shifting performance were extracted from each included study. If a study did not report adequate data, or if relevant data were only presented as graph, the corresponding author was contacted via email and data were requested. If the data request was not met but data were available as graph, the Web Plot Digitizer application was used to convert graphical into numerical data [38, 39]. This procedure was conducted because recent findings show that potential bias in meta-analyses can be reduced by including graphed data compared to excluding trials with only graphed data [40]. If data were not presented as figures and authors did not answer our data request, the trial could not be included.

In cases of multiple treatment arms eligible for inclusion in this review, data were combined following Higgins and Deeks' recommendations [41]. However, this was not the case for different exercise intensities because the potential moderation of exercise intensity was investigated. If participants were repeatedly tested, the corresponding author was contacted and raw data were requested. An overall mean of all time-points, eligible for inclusion in this review, was calculated from the raw data and used for meta-analysis [42]. If the data request was not met, we used the first measurement time-point succeeding treatment. Two members of the review team (M.O. and S.S.) independently conducted the data extraction. Any inconsistencies were resolved by discussion.

2.4 Quality Assessment of Included Studies

The methodological quality of the included studies was assessed using the Physiotherapy Evidence Database (PEDro) scale. Because the items "blinding of subjects" and "blinding of therapists" from the PEDro scale cannot be achieved in trials that investigate the effects of exercise interventions [43, 44], these items were disregarded. The following nine items were rated: (1) eligibility criteria, (2) random allocation, (3) concealed allocation, (4) baseline comparability, (5) blinding of assessors, (6) completeness of follow-up, (7) intention-to-treat-analysis, (8) between group statistical comparisons, and (9) point estimates and variability. Items were rated as having a "low risk of bias" if the criterions were clearly fulfilled. Items were rated as having a "high risk of bias" if the criterions were not met. If an article did not provide sufficient information or included contradicting, information concerning an item, it was rated as "unclear."

The PEDro summary score equals the number of items that were rated as low risk of bias with the exception of item 1. The PEDro summary score reflects the degree of a trial's internal validity. Item 1 is not included into the calculation of the summary score because it reflects external validity, instead of internal validity. Accordingly, the PEDro summary score for included studies ranged from one to eight points [45].

Two members of the review team (M.O. and S.S.) independently rated the methodological quality of included studies. The initial level of agreement between raters was excellent (intraclass correlation coefficient [ICC] = .92). Inconsistencies between raters were resolved by discussion.

2.5 Moderator Analyses

The 'degree of internal validity' measured by the PEDro summary score was examined for potential moderation of the effect of acute aerobic exercise on subsequent set shifting performance in healthy young adults. A meta-regression with PEDro summary score and included effects sizes was carried out.

The intensity of the applied exercise interventions was investigated for potential moderation. A subgroup analysis (light vs. moderate vs. vigorous aerobic exercise) was conducted.

2.6 Data Analyses

We followed the approach of Ludyga and colleagues [26] and analyzed effect size estimates obtained from time-dependent and accuracy measures of set shifting performance separately. Studies' effect size estimates were calculated by subtracting control group performance from exercise group performance. This means that concerning time-dependent measures, negative effect size estimates represent beneficial effects of acute aerobic exercise on subsequent set shifting performance. Concerning time-dependent measures, negative effect size estimates reflect faster completion of the test task following exercise compared to following control treatment. Concerning accuracy measures, positive effect size estimates represent beneficial effects of acute aerobic exercise on subsequent set shifting performance. Concerning time-dependent measures, negative effect size estimates reflect better accuracy in the test task after exercise compared to after control treatment.

The effect size estimate of each trial was calculated as bias corrected Hedges' g standardized mean difference (SMD). The SMD instead of the mean difference was used because it allows pooling of data from different testing procedures. Hedges' g values of .2, .5, and .8 were interpreted as small, moderate, and large effect sizes, respectively [46]. Post-values were used for SMD calculations because it was recommended not to combine change- and post-values together as SMDs [42] and several included studies only reported post-values.

Meta-analytic procedures were conducted in "R" using established guidelines [47]. A random effects model was used to pool outcomes across studies. Double counts were avoided by dividing the groups' sample sizes by the number of comparisons [41]. Between-study heterogeneity was quantified using the Higgins' I^2 statistic, which provides the proportion of real differences in effect sizes over total observed variance. I^2 values of 75%, 50%, and 25% were interpreted as large, moderate, and low proportion of between-study heterogeneity, respectively [48].

Sensitivity analyses were conducted to estimate the influence of outliers and the influence of studies, which mixed aerobic and anaerobic exercises. Outliers were defined as studies' effect size estimates whose confidence intervals did not overlap with the confidence interval of the summary effect size estimates [49]. To examine potential moderation of the after-effect of acute aerobic exercise on set shifting performance by the "degree of internal validity" measured by the PEDro summary score, meta-regression was conducted. The likelihood of a small-study effect was investigated using funnel plots and Egger's tests [29, 50]. To investigate potential moderation of exercise intensity, subgroup analyses were conducted.

3. Results

3.1 Selected Studies

The electronic database search resulted in 5,197 publications. Through the references of recent meta-analyses [26, 28, 37] and included studies, five additional records were identified. After duplicate removal, titles and abstracts of 3,582 publications were screened. At this process stage of the review, we excluded 3,562 records because the above defined eligibility criteria for inclusion in this review was not met. Next, full texts of the remaining 20 publications were retrieved and read. Here, we excluded eight studies because the applied cognitive tests did not measure set shifting performance. The PRISMA diagram that is presented in Figure 1 provides an overview of the selection process.

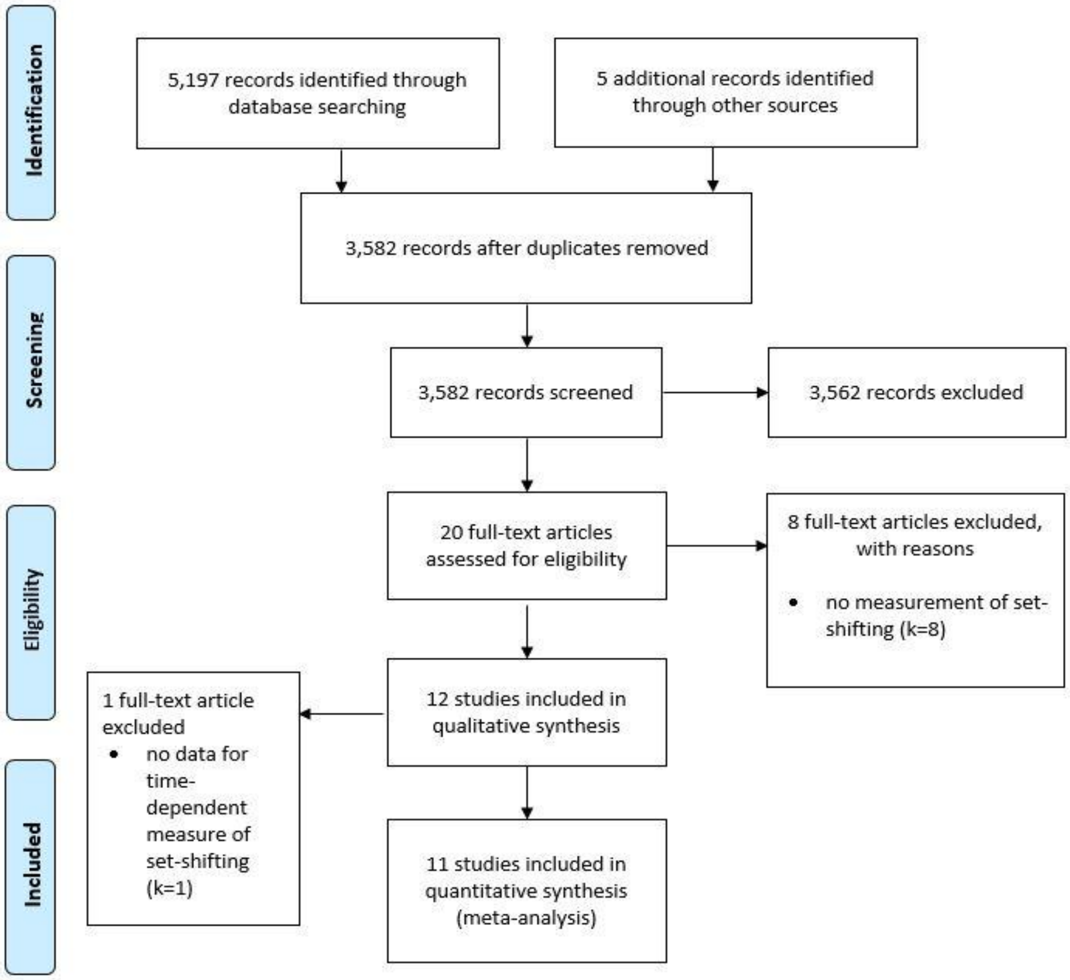

Figure 1 Flow chart of studies retrieved and screened to PRISMA guidelines.

3.2 Characteristics of Studies

Twelve studies, with data from 1,189 healthy young participants, were included in the qualitative synthesis. Of the 12 included studies, three applied a randomized controlled crossover design [51-53]. Nine studies applied a randomized controlled design [16, 22, 23, 25, 54-58]. Time dependent measures of set shifting performance were available for 11 included studies. However, only two studies reported accuracy measures for set shifting [8, 23]. Accordingly, meta-analytic procedures were only conducted for time-dependent measures of set shifting performance (k=11).

One of the 11 studies that we included in the meta-analysis comprised of two experiments. Both provided eligible data for meta-analysis (marked as Barenberg et al. 2015a and Barenberg et al. 2015b [51]). One study tested different exercise intensities against the same control group [16]. Each of these comparisons was included in the meta-analysis (double counting was avoided by dividing control group sample size by the number of comparisons). Accordingly, 14 effect size estimates were included in the meta-analysis. One study that we included in the meta-analysis divided exercise and control groups into different subgroups with regards to test timing (30, 60, 90, and 120 min. after treatment) [54]. One study applied two control groups eligible for inclusion [52]. One study had multiple exercise duration groups (10, 20, 30, and 45 min.) each divided by different test timings (5, 15, and 30 min. after treatment) [53]. For each of those studies, data from eligible study groups were combined as described above (see Section 2.3: Outcome Measures and Data Extraction). None of the included studies applied multiple outcomes for set shifting performance.

The exercise intervention in one study consisted of a 2-minute warm up at 25 watts, followed by an increase of 25 watts until exhaustion, a 3-minute active recovery period at 20 watts, a second increase until exhaustion, and finally a 3-minute recovery phase at 20 watts [51]. A second study conducted a 10-minute warm up at 50 watts, followed by ten maximal bouts of all out pedaling for 20 seconds against 5.5% of the subject's body weight, separated by a 10-second active rest period. The exercise regimens in these two studies are not entirely aerobic as they also have anaerobic elements; however, we decided to include these studies in the analysis and check their influence by conducting sensitivity analyses.

On average, the studies reached a PEDro summary score of 6.08 (SD = .29), which relates to a good methodological quality of included studies [59]. Table 1 gives a comprehensive summary of included studies’ characteristics. This also includes the PEDro summary scores. An overview of the study quality, rated with the PEDro scale, is presented in Figure 2.

3.2.1 Accuracy Measures of Set shifting Performance

Two studies reported the effects of acute aerobic exercise on subsequent accuracy measures of set shifting performance. Both studies report a beneficial effect of aerobic exercise. Slusher and colleagues [23] show a significant large beneficial effect size estimate for exercise compared to the control (Hedges’ g = .84, 95 % CI .04 to 1.65). However, Wang and colleagues [58] show only a small non-significant effect (Hedges’ g = .09, 95 % CI -.66 to .85). It should be noted that the study from Slusher and colleagues [23] applied a mixture of aerobic and anaerobic exercise. That makes it questionable if it is comparable with the other included studies (see 3.3 Meta-Analysis Results).

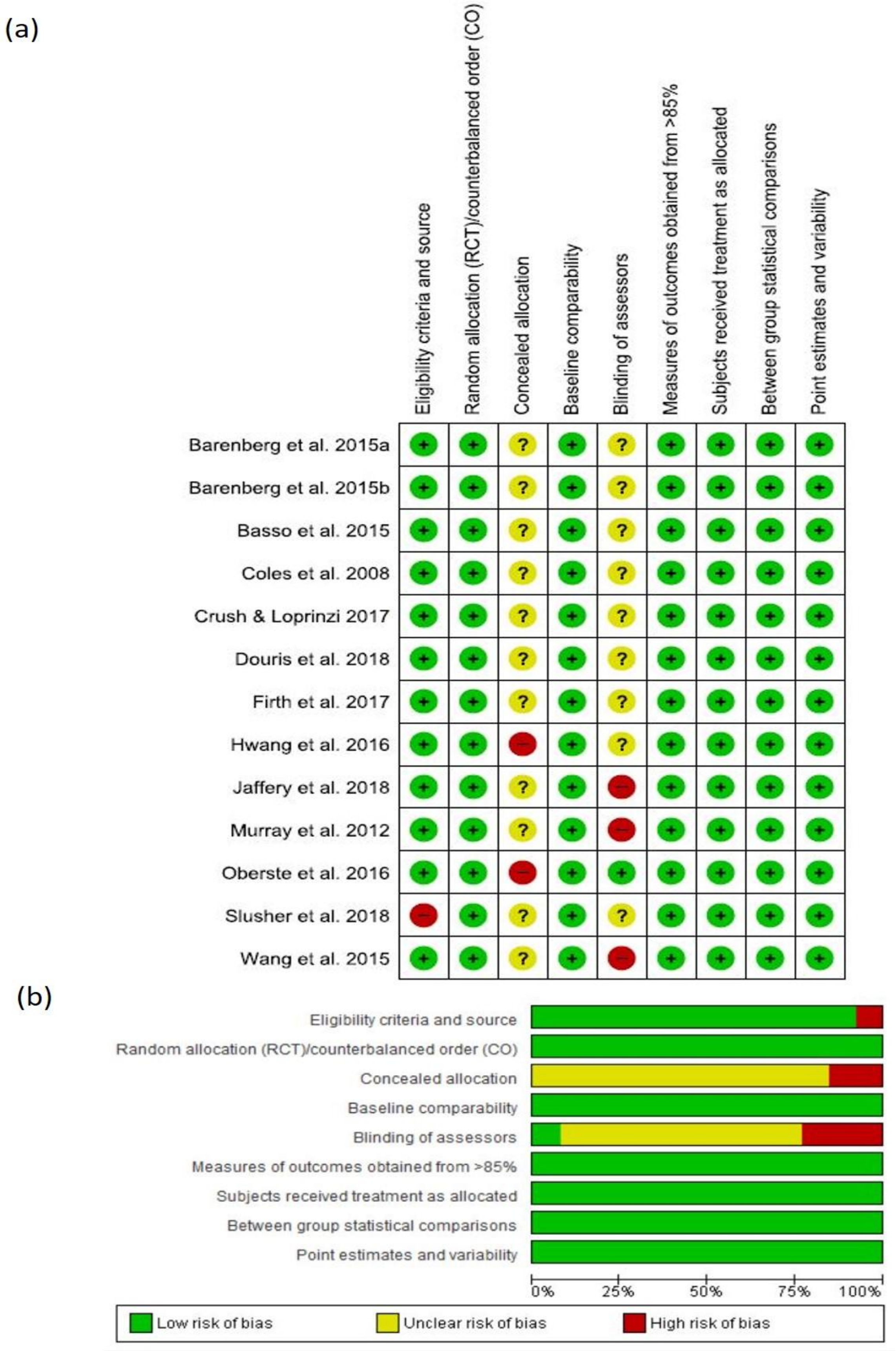

Figure 2 Risk of bias ratings. ((a) Risk of bias rating for each study; (b) Percentage of studies receiving low, high, or unclear risk of bias regarding each item).

Table 1 Overview of studies included into the systematic review and meta-analysis on the after-effect of acute aerobic exercise on set shifting performance in healthy young adults.

Study	**N/ Age**	**Study Design**	**Exercise treatment**	**Intensity**	**Control group treatment**	**Cognitive testing procedure**	**Type of variable to measure set shifting**	**PEDro summary score**
Barenberg et al. 2015a	• 24 (f) / 25 (m) • 24,45 ± 2,72y	• Crossover	• **approximately 10 min. ergometer cycling:** 2-min warm-up at 25 W, workload was increased by 25 W every 10 s until exhaustion or pace falling below 60 rpm., 3-minute active recovery phase, second run till exhaustion, 4-min recovery phase at 20 W	vigorous	• **10 min. listening to music**	• Switch trial test	• Time to complete task	• 6/8
Barenberg et al. 2015b	• 27 (f) / 18 (m) • 23,02 ± 1,71y	• Crossover	• **approximately 10 min ergometer cycling:** 2-min warm-up at 25 W, workload was increased by 25 W every 10 s until exhaustion or pace falling below 60 rpm., 3-minute active recovery phase, second run till exhaustion, 4-min recovery phase at 20 W	vigorous	• **10 min. seated rest** in a chair and listening to music	• Switch trial test	• Time to complete task	• **6**/8
Basso et al. 2015	• 51 (f) / 34 (m) • 20.78 ± 0.46y	• RCT	• **60 min. ergometer cycling:** 5 min. warm up, 50 min at 85% of maximum heart rate (220-age), 5 min. cool-down	vigorous	• **60 min. watching TV**	• Trail Making Task	• Time to complete task	• 6/8
Coles et al. 2008	• 18 (f+m) • 22,2 ± 1,6y	• Crossover	• **40 min. ergometer cycling:** 5 min. warm-up at 30% of VO_2max, 30 min. at 60% of VO_2max, 5 min. cool-down at 30% of VO_2max	moderate	• **40 min seated rest or watching TV**	• Visual switch task	• Time to complete task	• 6/8
Crush et al. 2017	• 239 (f) / 113 (m) • 21.05 ± 0.21y	• Crossover	• **10 min. running on treadmill** at 40% to 59% of HRR	moderate	• **Baseline**	• Trail Making Task	• Time to complete task	• 6/8
Douris et al. 2018	• 24 (f) / 14 (m) • 23,7 ± 1,8y	• RCT	• **30 min. ergometer cycling** at 60 to 70% of HR_{max}	moderate	• **30 min. seated rest**	• Trail Making Task	• Time to complete task	• 6/8
Frith et al. 2017	• 12 (f) / 10(m) • 21,9 ± 2,4y	• RCT	• **15 min. jogging on treadmill**: 5 min at an easy self-selected intensity, 5 min keeping the pace at an RPE of 13-15, 5 min keeping the pace at an RPE of 16-20	vigorous	• **20 min. seated rest**	• Trail Making Task	• Time to complete task	• 6/8

Hwang et al. 2016	• 32 (f) / 26 (m) • 23.59 ± 1.06y	• RCT	• **20 min. running on treadmill:** 2 min. warm up, 5 min. increased speed to reach target intensity, 10 min. running at 85–90% VO2max	vigorous	• **20 min. seated rest**	• Trail Making Task	• Time to complete task	• 6/8
Jaffery et al. 2018	• 64 (f) / 24 (m) • 21.5 ± 0.5y	• RCT	• **5 min. walking on treadmill** at a self-selected brisk walking pace	light	• **5-10 min. seated rest**	• Trail Making Task	• Time to complete task	• 6/8
Murray & Russoniello 2012	• 60 (f) / 60 (m) • 20.86 ± 0.27y	• RCT	• **30 min. ergometer cycling** at 75.46 % of HR_{max}	vigorous	• **Monitor and motivate participants from the exercise group**	• Trail Making Task	• Time to complete task	• 6/8
Oberste et al. 2016	• 37 (f) / 84 (m) • 23.92 ± 0.09y	• RCT	• **35 min. ergometer cycling:** 5 min. warm up 25 W, 30 min. at 45-50%, 65-70%, or 85-90% of HR_{max}.	light, moderate, and vigorous	• **35 min. instructed self-myofascial release session with foam roll**	• Trail Making Task	• Time to complete task	• 7/8
Slusher et al. 2018	• 13 (m) • 23,62 ± 1,06y	• RCT	• **15 min. ergometer cycling: 1**0 min. warm-up at 50W, low-volume, supramaximal HIIE (ten maximal bouts of all out pedaling for 20- seconds against 5.5% of the subject's body weight, separated by a 10-s active rest period)	vigorous	• **10 min. warm up, then 5 min seated rest**	• Wisconsin Card Sorting Task	• Time to complete task • Accuracy	• 6/8
Wang et al. 2015	• 19 (f) / 8 (m) • 22.67 ± 0.14y	• RCT	• **30 min. ergometer cycling:** 5 min. warm-up, 20 min at 65% of HRR, 5 min. cool down	vigorous	• **30 min. reading**	• Wisconsin Card Sorting Task	• Accuracy	6/8

3.3 Meta-Analysis Results

In the primary meta-analysis, 14 effect size estimates (n = 1,162) of the effect of acute aerobic exercise on subsequent time-dependent measures of set shifting performance compared to control groups in healthy young adults were pooled. A significant small to moderate beneficial after-effect of acute aerobic exercise (Hedges' g = -.26, 95 % CI -.49 to -.02, p = .03) with large true heterogeneity was revealed (I^2 = 70.9 %, Q = 44.61, p < .0001). Figure 3 shows a forest plot of the initial analysis.

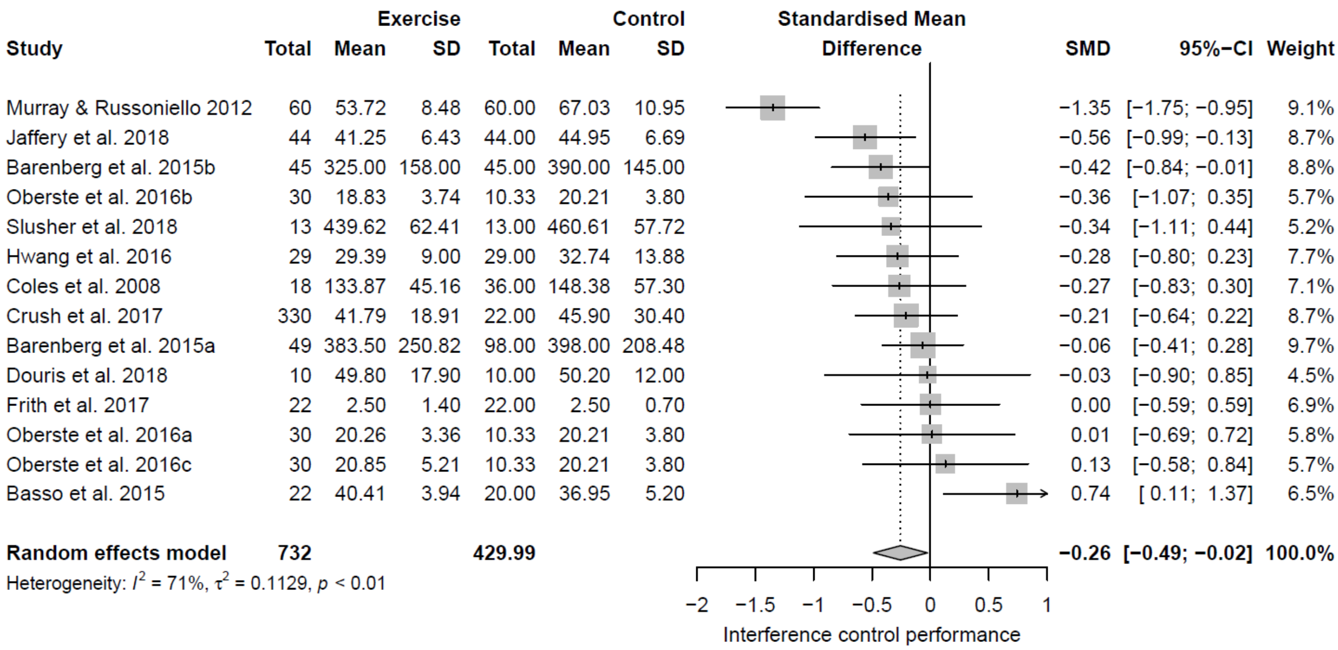

Figure 3 Forest plot of the after-effect of acute aerobic exercise on set shifting performance compared to control in healthy young adults.

We investigated the potential presence of small study effect by scattering the SMDs from each individual study against its precision (standard error) in a funnel plot. Visual inspection of the funnel plot, depicted in Figure 4, did not reveal obvious asymmetry. This visual impression was supported by a non-significant Egger's regression (Egger`s intercept = -.96, p = .18).

Forest and funnel plots clearly show two study effect size estimates, whose confidence intervals do not overlap with the confidence interval of the summary effect size estimate. These effect size estimates are by definition outliers (see 2.3 Data Analysis). One of the outliers, the study from Murray and Russoniello [24], shows an effect size estimate that exceeds the summary effect size estimate by about one standard deviation. The second outlier, the study from Basso and colleagues [54], shows an effect size estimate that is about one standard deviation less than the summary effect size estimate. Sensitivity analysis using a dataset without the two outliers slightly reduced the magnitude of the summary effect size estimate (Hedges' g = -.23, 95 % CI -.38 to -.-.08, p = .003). The heterogeneity was substantially reduced (I^2 = 0%, Q = 6.52, p=.84). Comparison of the Q-tests of heterogeneity with and without outliers (k = 12, Q = 44.61, p < .0001 and k = 12, Q = 6.52, p = .84) shows the significant effect of the two outliers on the in-between studies variability.

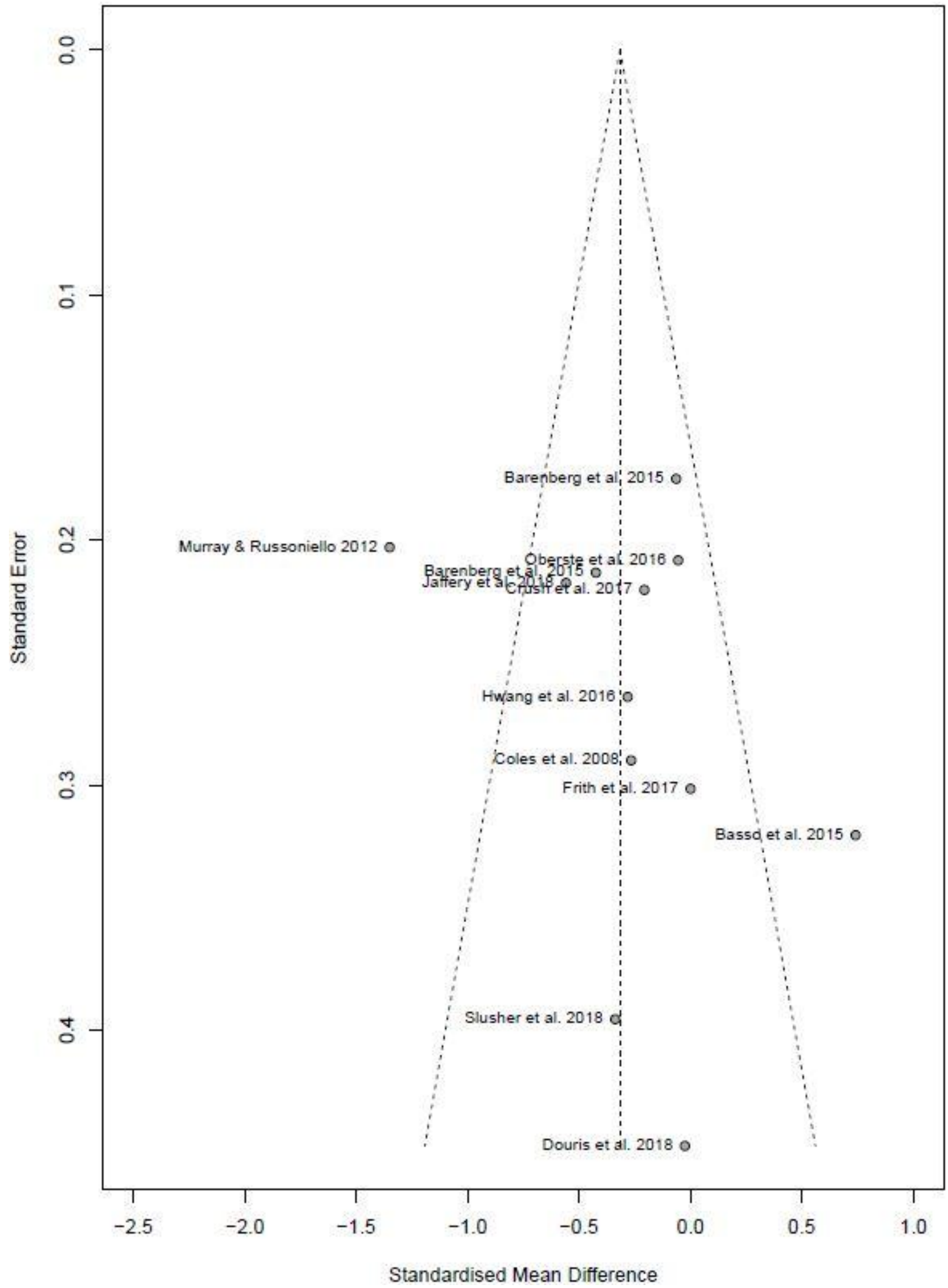

Figure 4 Funnel plot of effect sizes estimates of the after-effect of acute aerobic exercise on set shifting performance compared to control in healthy young individuals.

The studies from Barenberg and colleagues and from Slusher and colleagues can be considered a mixture of aerobic and anaerobic exercise. However, sensitivity analysis using the dataset without these studies did not change the results (Hedges' g = -.24, 95 % CI -.54 to 05, p = .11). The heterogeneity was not reduced (I^2 = 76.2%, Q = 42.02, p < .0001).

The hypothesis that the effect of acute aerobic exercise on subsequent set shifting performance is moderated by the "degree of internal validity" (measured via PEDro summary score) was not supported by the results of the conducted meta-regression. Neither with the full data set (k = 12) (R^2 = .00, p = .44) nor with the reduced data set (without outliers, k=10) (R^2 = .00, p = .91) was the effect of acute aerobic exercise on subsequent set shifting performance predicted by PEDro summary score.

Subgroup analysis revealed no significant difference between aggregated effect sizes of studies that applied exercise at light, moderate, or vigorous intensity (Q-between=0.60, df = 2, p = .74). Pooling of data from studies that applied light intensity exercise resulted in a small averaged effect size (k = 2, Hedges' g = -.34, 95% CI = -.89 to .20). Pooling of data from studies that used moderate exercise showed also a small effect (k = 4, Hedges' g = -.23, 95% CI = -.52 to .06). Pooling of data from studies that applied vigorous exercise resulted also in a small effect (k = 8, Hedges' g = -.23, 95% CI = -.63 to .18).

4. Discussion

This meta-analysis showed that even healthy young adults, who are at the peak of their physiological and cognitive capacities, show improved set shifting performance after a single bout of aerobic exercise. The magnitude of the summary effect size estimate (Hedges' g = -.26) refers to a small to moderate effect following Cohen's classification [46]. However, interpretation of this effect size estimate is easier if it is re-expressed in the units of a familiar scale. This can be achieved if the summary SMD is multiplied by a "typical standard deviation" of that familiar scale. If the standard deviation of the control group of the included study with the largest sample size ([60]) is used as "typical standard deviation," and if the time to finish the Trail Making Test part B is used as familiar scale, a mean time benefit of 8.2 seconds due to preceding exercise compared to control is revealed. The practical importance of this benefit of set shifting performance must be determined on a case to case basis. In situations with a high demand for fast reactions, while one has to shift attention from one attribute of a stimulus to another, a small speed advantage might make a decisive difference. But this remains speculative.

One should consider that the 95% confidence interval of the summary effect size estimate from the initial analysis is wide (95 % CI -.53 to -.00). It ranges from practically no effect to a moderate to large effect. Homogeneity of the initial analysis is also large. However, sensitivity analysis revealed that this variation is mainly because of two studies providing diametrically opposed outliers [24, 54]. When these two outliers were taken out of the analysis, the confidence interval decreased and results became homogenous. If one takes a closer look at the two studies that provided the two outliers there are possible explanations for the deviating effect size estimates. The study that exceeded the summary effect size estimate by far ([22]) had control group participants supervise and motivate the exercise session of the exercise group participants. Potentially, this procedure has made the hypothesis of the design (exercise induced cognitive facilitation) so clear to the participants, that expectation driven placebo effects and/or confirmation bias resulted in the very large beneficial effect. In the other outlier study that provided a significant detrimental effect size estimate ([61]), participants were cycling one hour at vigorous intensity. Potentially, this exercise regimen was inducing fatigue and dehydration. It was shown that exercise-induced fatigue and dehydration can have a detrimental effects on cognitive performance [62].

The average methodological quality of the included studies was good. With one exception ([23]), risk of bias in the included studies was exclusively due to a lack of allocation concealment and blinding of assessors. Because none of the included studies clearly fulfilled the criterion of allocation concealment and only one study ([16]) was conducted with blinding of assessors, subgroup analyses regarding these methodological factors were not possible. However, the overall methodological quality, measured via the PEDro summary score, did not predict the magnitude of studies' effect size estimates. Future empirical studies that investigate the effect of acute exercise on subsequent set shifting performance should apply concealed allocation and blinding of assessors to increase internal validity of research and to eliminate remaining doubts on beneficial after-effects in healthy young adults.

Exercise intensity did not moderate the magnitude of studies' effect size estimates. This result is quite surprising because physiological measures, which are discussed as underlying exercise-induced cognitive benefits, are associated with exercise intensity. Potentially, in healthy young adults, psychological mechanisms rather than physiological adaptation to the exercise underlie beneficial cognitive effects of exercise. Psychological effects of exercise are less associated with exercise intensity [27]. However, one should consider that only two of the included studies applied light intensity.

In this systematic review, we could not find support for the hypothesis that beneficial effects of acute aerobic exercise on subsequent set shifting performance in healthy young adults are a result of small-study effect. Accordingly, publication bias appears highly unlikely to explain exercise induced benefits of set shifting healthy young adults.

The presented results here must be interpreted against the background of limitations. First, in this meta-analysis, several durations of exercise treatments were analyzed together. It cannot be ruled out that the magnitude of the effect of acute aerobic exercise on subsequent set shifting performance in young healthy adults varies with varying exercise durations.

Second, we were not able to analyze accuracy measures quantitatively in this review. This is problematic in terms of interpretation of results. It cannot be ruled out that faster reaction time is a consequence basic information processing speed and motor reaction speed facilitation instead of an improvement of set shifting. It can also not be ruled out that reported benefits in time-dependent measures are due to a speed-accuracy trade-off. This means that participants would show a stronger tendency to sacrifice accuracy of responses to achieve a higher answering speed following exercise compared to following control treatment [26]. However, contradictory to this alternative explanation is the finding that healthy young participants usually show ceiling effects concerning accuracy measures of set shifting.

Third, there are other methodological issues that might moderate the effect of acute aerobic exercise on subsequent set shifting performance. Training effects with the neuropsychological test procedure are one important issue. Here, we included studies regardless of the usage of familiarization with the test procedure or usage of parallel forms. Future research should examine the influence of that potential methodological shortcoming.

5. Conclusions

This meta-analysis showed that even healthy young individuals improve set shifting performance following a single bout aerobic exercise. The evidence provided in this review indicates that these effects are unlikely the result of methodological shortcomings, exercise intensity, or small-study effect. Therefore, it seems highly probable that acute aerobic exercise-induced set shifting performance benefits are due to physiological and/or psychological adaptations to the exercise. The practical relevance is difficult to evaluate but might be given in context with high demand for fast reactions while resolving interference by distracting stimuli.

Acknowledgments

The authors thank Rozeta Levkovska for formatting support.

Author Contributions

Max Oberste did the analysis and wrote the manuscript. Sophia Sharma and Max Oberste conducted the literature search and the quality rating of the included studies. Philipp Zimmer proofread the manuscript and provided support for the analysis.

Competing Interests

The authors have declared that no competing interests exist.

References

1. Minzenberg MJ, Laird AR, Thelen S, Carter CS, Glahn DC. Meta-analysis of 41 functional neuroimaging studies of executive function in schizophrenia. Arch Gen Psychiatry. 2009; 66: 811-822.
2. Pontifex MB, McGowan AL, Chandler MC, Gwizdala KL, Parks AC, Fenn K, et al. A primer on investigating the after effects of acute bouts of physical activity on cognition. Psychol Sport Exerc. 2019; 40: 1-22.
3. Diamond A. Executive functions. Annu Rev Psychol. 2013; 64: 135-168.
4. Endo K, Matsukawa K, Liang N, Nakatsuka C, Tsuchimochi H, Okamura H, et al. Dynamic exercise improves cognitive function in association with increased prefrontal oxygenation. J Physiol Sci JPS. 2013; 63: 287-298.
5. Querido JS, Sheel AW. Regulation of cerebral blood flow during exercise. Sports Med. 2007.
6. Van Hall G. Lactate kinetics in human tissues at rest and during exercise. Acta Physiol. 2010; 199: 499-508.
7. Dalsgaard MK, Quistorff B, Danielsen ER, Selmer C, Vogelsang T, Secher NH. A reduced cerebral metabolic ratio in exercise reflects metabolism and not accumulation of lactate within the human brain. J Physiol. 2004; 554: 571-578.
8. Weng TB, Pierce GL, Darling WG, Voss MW. Differential effects of acute exercise on distinct aspects of executive function. Med Sci Sports Exerc. 2015; 47: 1460-1469.

9. Davidson MC, Amso D, Anderson LC, Diamond A. Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. Neuropsychologia. 2006; 44: 2037-2078.
10. Daamen M, Raab M. Psychological assessments in physical exercise. In: Boecker H, Hillmann CH, Scheef L, Strüder HK, editors. Functional Neuroimaging in Exercise and Sport Sciences. New York: Springer; 2012. p. 109-153.
11. Chang YK, Liu S, Yu HH, Lee YH. Effect of acute exercise on executive function in children with attention deficit hyperactivity disorder. Arch Clin Neuropsychol Off J Natl Acad Neuropsychol. 2012; 27: 225-237.
12. Chang YK, Labban JD, Gapin JI, Etnier JL. The effects of acute exercise on cognitive performance: A meta-analysis. Brain Res. 2012; 1453: 87-101.
13. Córdova C, Silva VC, Moraes CF, Simões HG, Nóbrega OT. Acute exercise performed close to the anaerobic threshold improves cognitive performance in elderly females. Brazilian J Med Biol Res. 2009; 42: 458-464.
14. Naderi A, Shaabani F, Esmaeili A, Salman Z, Borella E, Degens H. Effects of low and moderate acute resistance exercise on executive function in community-living older adults. Sport Exerc Perform Psychol. 2019; 8: 106-122.
15. Pirrie AM, Lodewyk KR. Investigating links between moderate-to-vigorous physical activity and cognitive performance in elementary school students. Ment Health Phys Act. 2012; 5: 93-98.
16. Oberste M, Bloch W, Hübner ST, Zimmer P. Do reported effects of acute aerobic exercise on subsequent higher cognitive performances remain if tested against an instructed self-myofascial release training control group? A randomized controlled trial. PLoS One. 2016; 11: e0167818.
17. Gajewski PD, Ferdinand NK, Kray J, Falkenstein M. Understanding sources of adult age differences in task switching: Evidence from behavioral and ERP studies. Neurosci Biobehav Rev. 2018; 92: 255-275.
18. Stillman CM, Watt JC, Grove Jr GA, Wollam ME, Uyar F, Mataro M, et al. Physical activity is associated with reduced implicit learning but enhanced relational memory and executive functioning in young adults. PLoS One. 2016; 11: e0162100.
19. Whitley E, Deary IJ, Ritchie SJ, Batty GD, Kumari M, Benzeval M. Variations in cognitive abilities across the life course: Cross-sectional evidence from Understanding Society: The UK Household Longitudinal Study. Intelligence. 2016; 59: 39-50.
20. Drollette ES, Scudder MR, Raine LB, Moore RD, Saliba BJ, Pontifex MB, et al. Acute exercise facilitates brain function and cognition in children who need it most: An ERP study of individual differences in inhibitory control capacity. Dev Cogn Neurosci. 2014; 7: 53-64.
21. Sibley BA, Beilock SL. Exercise and working memory: An individual differences investigation. J Sport Exerc Psychol. 2007; 29: 783-791.
22. Murray NP, Russoniello C. Acute physical activity on cognitive function: A heart rate variability examination. Appl Psychophysiol Biofeedback. 2012; 37: 219-227.
23. Slusher AL, Patterson VT, Schwartz CS, Acevedo EO. Impact of high intensity interval exercise on executive function and brain derived neurotrophic factor in healthy college aged males. Physiol Behav. 2018; 191: 116-122.
24. Murray NP, Russoniello C. Acute physical activity on cognitive function: A heart rate variability examination. Appl Psychophysiol Biofeedback. 2012; 37: 219-227.

25. Frith E, Sng E, Loprinzi PD. Randomized controlled trial evaluating the temporal effects of high-intensity exercise on learning, short-term and long-term memory, and prospective memory. Eur J Neurosci. 2017; 46: 2557-2564.
26. Ludyga S, Gerber M, Brand S, Holsboer-Trachsler E, Pühse U. Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. Psychophysiology. 2016; 53: 1611-1626.
27. Szabo A. Acute psychological benefits of exercise: Reconsideration of the placebo effect. J Ment Health. 2013; 22: 449-455.
28. Verburgh L, Konigs M, Scherder EJA, Oosterlaan J. Physical exercise and executive functions in preadolescent children, adolescents and young adults: A meta-analysis. Br J Sports Med. 2014; 48: 973-979.
29. Sterne JAC, Sutton AJ, Ioannidis JPA, Terrin N, Jones DR, Lau J, et al. Recommendations for examining and interpreting funnel plot asymmetry in meta-analyses of randomised controlled trials. BMJ. 2011; 343: 1-8.
30. Dickersin K, Min Y. Publication bias: The problem that won't go away. Ann N Y Acad Sci. 1993.
31. Moher D, Liberati A, Tetzlaff J, Altman DG, Group TP. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Plos Med. 2009; 6: e1000097.
32. Moher D, Shamseer L, Clarke M, Ghersi D, Liberati A, Petticrew M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev. 2015; 4: 1.
33. Wahid A, Manek N, Nichols M, Kelly P, Foster C, Webster P, et al. Quantifying the association between physical activity and cardiovascular disease and diabetes: A systematic review and meta-analysis. J Am Heart Assoc. 2016; 5: e002495.
34. Norton K, Norton L, Sadgrove D. Position statement on physical activity and exercise intensity terminology. J Sci Med Sport. 2010; 13: 496-502.
35. Seiferth NY, Thienel R, Kircher T. Exekutive Funktionen. In: Schneider F, Fink GR, editors. Funktionelle MRT in Psychiatrie und Neurologie. Berlin, Heidelberg: Springer Berlin Heidelberg; 2007. p. 265-277.
36. Basso JC, Shang A, Elman M, Karmouta R, Suzuki WA. Acute exercise improves prefrontal cortex but not hippocampal function in healthy adults. J Int Neuropsychol Soc. 2015; 21: 791-801.
37. Chang YK, Labban JD, Gapin JI, Etnier JL. The effects of acute exercise on cognitive performance: A meta-analysis. Brain Res. 2012; 1453: 87-101.
38. Tsafnat G, Glasziou P, Choong MK, Dunn A, Galgani F, Coiera E. Systematic review automation technologies. Syst Rev. 2014; 3: 1-15.
39. Rothagi A. Web Plot Digitizer. 2013. http://arohatgi.info/WebPlotDigitizer/.
40. Vucic K, Jelicic Kadic A, Puljak L. Survey of Cochrane protocols found methods for data extraction from figures not mentioned or unclear. J Clin Epidemiol. 2015; 68: 1161-1164.
41. Higgins JP, Deeks JJ. Selecting Studies and Collecting Data. In: Higgins JP, Green S, editors. Cochrane Handbook for Systematic Reviews of Interventions version 5.1.0. The Cochrane Collaboration; 2011. doi:10.1002/9780470712184.ch7.
42. Deeks JJ. Chapter 9: Analysing data and undertaking. In: Higgins JP, Churchill R, Chandler J, S CM, editors. Cochrane Handbook for Systematic Reviews of Interventions version 5.2.0. The Cochrane Collaboration; 2017. www.cochrane-handbook.org.

43. Morton NA De. The PEDro scale is a valid measure of the methodological quality of clinical trials : A demographic study. Aust J Physiother. 2009; 55: 129-133.
44. Cumming RG, Sherrington C, Lord SR, Simpson JM, Vogler C, Cameron ID, et al. Cluster randomised trial of a targeted multifactorial intervention to prevent falls among older people in hospital. BMJ. 2008; 336: 758-760.
45. Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins M. Reliability of the PEDro scale for rating quality of randomized controlled trials. Phys Ther. 2003; 83: 713-721.
46. Cohen J. Statistical Power Analysis for the Behavioral Sciences. 2nd ed. Hoboken: Taylor and Francis; 2013. http://gbv.eblib.com/patron/FullRecord.aspx?p=1192162.
47. Schwarzer G, Carpenter JR, Rücker G. Meta- Analysis with R. Heidelberg: Springer; 2015.
48. Higgins JP, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses Testing for heterogeneity. BMJ. 2003; 327: 557-560.
49. Viechtbauer W, Cheung MW-L. Outlier and influence diagnostics for meta-analysis. Res Synth Methods. 2010; 1: 112-125.
50. Egger M, Davey Smith G, Schneider M, Minder C, Smith GD. Bias in meta-analysis detected by a simple, graphical test. Br Med J. 1997; 7109: 629-634.
51. Barenberg J, Berse T, Dutke S. Ergometer cycling enhances executive control in task switching. J Cogn Psychol. 2015; 27: 692-703.
52. Coles K, Tomporowski PD. Effects of acute exercise on executive processing, short-term and long-term memory. J Sports Sci. 2008; 26: 333-344.
53. Crush EA, Loprinzi PD. Dose-response effects of exercise duration and recovery on cognitive functioning. Percept Mot Skills. 2017; 124: 1164-1193.
54. Basso JC, Shang A, Elman M, Karmouta R, Suzuki WA. Acute exercise improves prefrontal cortex but not hippocampal function in healthy adults. J Int Neuropsychol Soc. 2015; 21: 791-801.
55. Douris PC, Handrakis JP, Apergis D, Mangus RB, Patel R, Limtao J, et al. The effects of aerobic exercise and gaming on cognitive performance. J Hum Kinet. 2018; 61: 73-83.
56. Hwang J, Brothers RM, Castelli DM, Glowacki EM, Chen YT, Salinas MM, et al. Acute high-intensity exercise-induced cognitive enhancement and brain-derived neurotrophic factor in young, healthy adults. Neurosci Lett. 2016; 630: 247-253.
57. Jaffery A, Edwards MK, Loprinzi PD. The effects of acute exercise on cognitive function: Solomon experimental design. J Prim Prev. 2018; 39: 37-46.
58. Wang C. Failure to identify an acute exercise effect on executive function assessed by the Wisconsin Card Sorting Test. J Sport Heal Sci. 2014; 2015: 1-9.
59. Teasell R, Reekum R Van, Aubut J-A, Salter K, Rees L, Foley N, et al. A systematic review of the rehabilitation of moderate to severe acquired brain injuries. Brain Inj. 2007; 21: 107-112.
60. Crush EA, Loprinzi PD. Dose-response effects of exercise duration and recovery on cognitive functioning. Percept Mot Skills. 2017; 124: 1164-1193.
61. Basso JC, Shang A, Elman M, Karmouta R, Suzuki WA. Acute exercise improves prefrontal cortex but not hippocampal function in healthy adults. J Int Neuropsychol Soc. 2015; 21: 791-801.
62. Cian C, Barraud PA, Melin B, Raphel C. Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. Int J Psychophysiol. 2001; 42: 243-251.


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