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The effects of acute aerobic exercise on executive function: A systematic review and meta-analysis of individual participant data

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ABSTRACT

An increasing number of studies has focused on the after-effects of acute aerobic exercise on executive function. To date, empirical evidence lacks consensus regarding whether acute aerobic exercise has beneficial effects on executive function. To identify possible sources of this discrepancy, the present study focused on executive function demands and pre-test cognitive performance, and performed the first meta-analysis of individual participant data (IPD meta-analysis) in this area of research. Results indicated that the beneficial after-effects of acute aerobic exercise on cognitive performance were greater in participants with lower cognitive performance at pre-test. Acute aerobic exercise offered general benefits to cognitive performance irrespective of executive function demands, when pre-test cognitive performance was appropriately controlled. Thus, the present IPD meta-analysis suggests that pre-test cognitive performance is one possible source of the conflicting findings in acute exercise studies. Future research is encouraged to consider pre-test cognitive performance to avoid underestimating the beneficial after-effects of acute exercise.

1. Introduction

Over the last two decades, increasing interest has focused on the effects of a single bout (i.e., "dose") of exercise on cognitive function (Ludyga et al., 2016; Pontifex et al., 2019). Since Colcombe and Kramer's (2003) seminal meta-analysis revealed that the beneficial effects of long-term exercise are selectively and disproportionately greater for higher-order cognitive functions, namely executive functions (EFs), the majority of acute exercise studies have since focused on this prefrontal-dependent aspect of cognition (Koechlin and Summerfield, 2007). EF refers to goal-directed cognitive processes that coordinate and regulate thought and action. Based on the recent framework by Miyake and Friedman (2012), inhibitory control (i.e., inhibition of thoughts, feelings and actions as well as resistance to distractors) is regarded as a common component of EF, whereas working memory (i.e., working with information mentally) and cognitive flexibility (i.e., shift between mental sets) appear to be separable components. That is, EFs are generally thought to comprise a common (inhibitory control) and two separable components (working memory and cognitive flexibility) (Best and Miller, 2010; Blair, 2016; Miyake and Friedman, 2012; Zink et al., 2021). Several meta-analyses that focused on EFs have shown a small but statistically significant beneficial after-effect of acute exercise on EFs (Ludyga et al., 2016; Moreau and Chou, 2019). However, visual inspection of the forest plots in these meta-analyses revealed that some studies have failed to find such beneficial effects. In fact, a recent meta-analysis did not find statistically beneficial effects of acute exercise on EFs (de Greeff et al., 2018). Resolving this discrepancy is of critical importance to guiding future research directions, such as identifying effective acute exercise doses, determine suitable cognitive tasks, and clarify the underlying mechanisms, since acute exercise has utility for in-school and in-workplace interventions to promote cognitive performance, learning, and work productivity (Heemskerk et al., 2020; Mullane et al., 2017).

The source of the conflicting findings in acute exercise research has been poorly understood. In an effort to identify possible sources, in the present study, we focused on EF demands and baseline (i.e., pre-test) cognitive performance, and conducted the first meta-analysis of individual participant data (IPD meta-analysis) in this area of research.

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Empirical evidence lacks consensus regarding whether acute exercise offers general benefits across multiple aspects of cognition or is selectively and disproportionately beneficial to EFs (e.g., Drollette et al., 2012; Ludyga et al., 2017; Pontifex et al., 2009; Weng et al., 2015). An additional factor that has demonstrated importance for the effects of acute aerobic exercise on cognition is baseline cognitive performance. Drollette et al. (2014) employed a within-participants crossover posttest comparison design, and bifurcated preadolescent participants into two groups (i.e., lower-performers and higher-performers) based on their flanker task performance in a non-exercise control condition (i.e., baseline performance), and indicated that the beneficial effects of acute exercise on cognitive performance were greater for the lower- relative to the higher-performers. This is supported by prior studies investigating different age groups and EF tasks (Crush and Loprinzi, 2017; Sibley and Beilock, 2007). Thus, the effects of acute exercise on cognitive function are likely to vary as a function of baseline performance. In the present IPD meta-analysis, we only focused on studies using the most rigorous study design (i.e., within-participants crossover pre-test post-test comparison designs; Pontifex et al., 2019). Because the effect of learning/practice via repeated exposure to the cognitive task can obscure the effects of acute exercise, the rigorous study design is considered to be suitable to examine the effects of acute exercise (Pontifex et al., 2019). As such, hereafter, baseline performance is referred to as “pre-test performance”. Given that evidence regarding the moderating role of pre-test performance has remained scarce, the present IPD meta-analysis focused pre-test performance as one possible moderator of the effects of acute exercise on EFs.

Note that task conditions requiring higher EF demands (referred to as “higher-EF condition” hereafter) should induce lower pre-test performance relative to task conditions necessitating lower EF demands (referred to as “lower-EF condition” hereafter). Based on the above studies that examined the moderating role of pre-test performance (Crush and Loprinzi, 2017; Drollette et al., 2014; Sibley and Beilock, 2007), lower pre-test performance should be related to larger beneficial effects of acute exercise. That is, greater beneficial effects of acute exercise are predicted in the higher-EF condition, possibly due not only to greater EF demand, but also due to lower pre-test performance. Collectively, the general versus specific nature of the effects of acute exercise on EF demand needs to be examined in a manner that accounts for the amount of EF required (i.e., EF condition) and individual differences in pre-test performance. To test the moderating roles of EF condition and pre-test performance, in the present study, multilevel modeling examined interactions between session (control and exercise) and EF condition (lower-EF and higher-EF demand) as well as between session and pre-test performance, respectively. The aim of these analyses is to reveal whether the beneficial effects of acute exercise on cognitive performance are greater for the higher-EF condition and for lower-performers at pre-test. If both interactions are found significant, the final model examines these two interactions simultaneously to statistically reveal whether the disproportionate effects are attributable to one factor or to differences between EF condition and pre-test performance.

Notably, the IPD meta-analysis approach has the advantage of determining the moderating roles of EF condition and pre-test performance on the effects of acute exercise on cognitive performance. Obviously, pre-test performance, which includes difference between EF conditions, should differ substantially between individuals even within a study. Non-IPD meta-analysis, which is based on comparisons among studies, cannot consider these individual differences. By contrast, IPD meta-analysis allows for comparisons of pre-test performance within a study, and thus the IPD approach is considered more suitable for examining the moderating roles of EF condition and pre-test performance.

The aim of the present study was to identify possible sources of the conflicting findings of acute exercise studies by focusing on the moderating roles of EF condition and pre-test performance. Due to a lack of consensus in the literature (Chang et al., 2012; de Greeff et al., 2018; Ludyga et al., 2016; Moreau and Chou, 2019), we did not make a specific prediction about whether the beneficial effects of acute exercise on cognitive performance would be observed generally across EF conditions or selectively for the higher-EF condition. The present IPD meta-analysis further extended our understanding of the general versus specific nature of the effects of acute exercise by investigating of the moderating roles of EF condition and pre-test performance simultaneously.

2. Methods

This IPD meta-analysis was pre-registered at PROSPERO (CRD42019125265) and the literature search was conducted following the guidelines established by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis of IPD (PRISMA-IPD) statement (Shamseer et al., 2015). The PRISMA-IPD checklist is provided as supplementary material.

2.1. Literature search

The PRISMA-IPD flow diagram showing the results of the literature search is provided in Fig. 1. The literature search was conducted up to November 30, 2020 using the following electronic bibliographic databases: PsycArticles, PsycINFO, PubMed, MEDLINE, Scopus, and EMBASE. To identify relevant studies, the search terms “acute,” “aerobic exercise,” and “physical activity” were combined with “accuracy,” “central executive,” “cognition,” “cognitive flexibility,” “cognitive function,” “cognitive performance,” “executive function,” “Flanker task,” “inhibition,” “reaction time,” “response time,” “short-term memory,” “Simon task,” “Sternberg task,” “Stroop task,” “task switching,” Tower of London,” “Trail Making Test,” “Wisconsin Card Sorting task,” and “working memory” (see Supplementary Table 1 for an example of search syntax). Additionally, the reference lists of relevant studies were also used to locate investigations matching the inclusion criteria. Only peer-reviewed studies published in English and indexed in one of the defined databases were considered for further analysis.

2.2. Study selection

Retrieved studies were assessed using the following inclusion and exclusion criteria.

2.2.1. Inclusion criteria

i Participants: no restrictions.
ii Study design: using the most rigorous study design (i.e., within-participants crossover pre-post comparison design; Pontifex et al., 2019), and using EF tasks that included at least two task conditions requiring variable EF demands (i.e., lower-EF and higher-EF condition).
iii Intervention: acute aerobic exercise. We only focused on aerobic exercise, which has been the most frequently employed acute exercise intervention in the literature (approximately 90 % of studies; Pontifex et al., 2019), to eliminate possible moderating roles of exercise modality on the effects of acute exercise on cognition.
iv Main outcome: pre-post changes in reaction time (RT) and/or accuracy.
v Language: only English.

2.2.2. Exclusion criteria

i Studies with no control session.
ii Studies of low quality (two or more high-risk bias points).

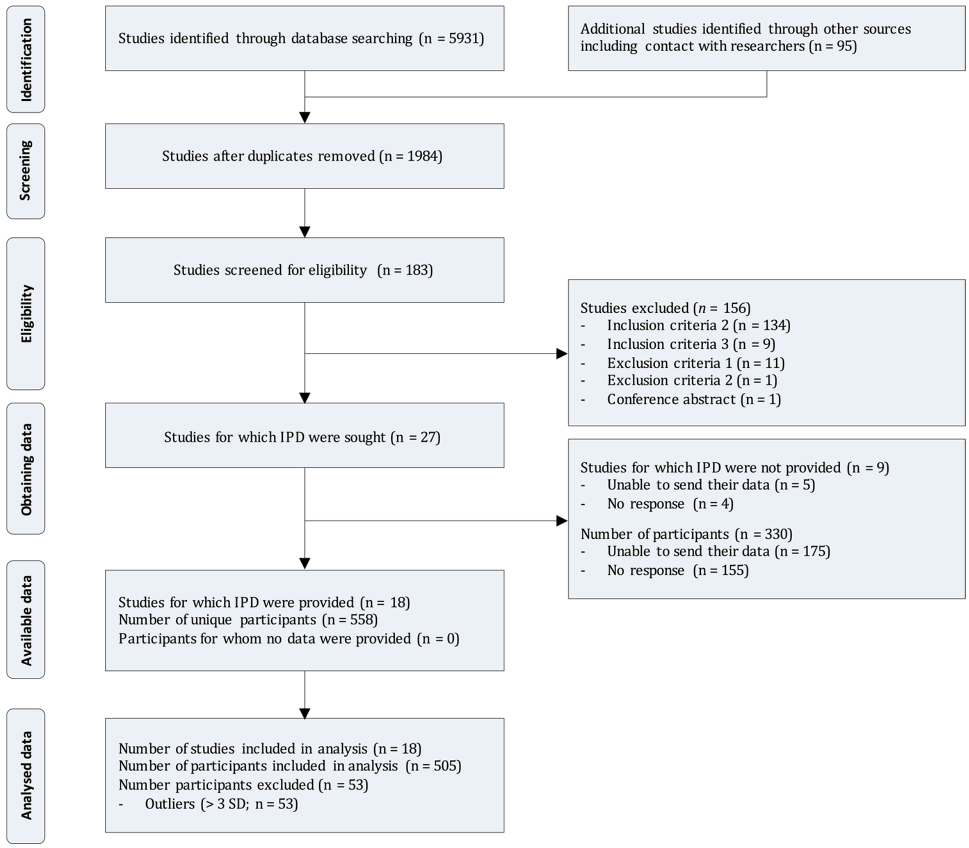

Fig. 1. PRISMA-IPD flow diagram showing the results of the literature search.

2.3. Screening

Two authors (T.I. and E.D.) independently screened the titles and abstracts of retrieved studies identified by the above search strategy. In a second step, these potentially eligible studies were re-evaluated in the full texts. In case of disagreement, a third author (S.L.) was consulted after reading the full texts.

2.4. Data extraction

We requested IPD from the authors for each eligible study and one author (T.I.) extracted the cognitive performance data (RT and/or accuracy) for each time (pre- and post-test), session (control and exercise), and EF condition (lower-EF and higher-EF condition). Reasons for why IPD were not provided are shown in Fig. 1. One author (T.I.) extracted the following data from each candidate article: (i) characteristics of trial participants (number, age, and sex); (ii) intervention features (e.g., duration, modality, and intensity); (iii) cognitive tasks and evaluated EF components (inhibition, working memory, or cognitive flexibility); and (iv) main results of outcomes. The data were then independently checked by a second author (K.K.).

2.5. Risk of bias (quality) assessment

For the assessment of methodological quality, two authors (T.I. and E.D.) individually evaluated the methodological quality of each study according to the following modified Physiotherapy Evidence Database (PEDro) scale. In cases of disagreement, a third author (S.L.) was consulted after reading the full texts.

i Participants were randomly allocated to groups (e.g., control session first or exercise session first).
ii The session order was counterbalanced.
iii Measures of at least one key outcome were obtained from more than 85 % of the participants initially allocated to groups.
iv The results of between-session statistical comparisons were reported for at least one key outcome.

2.6. Statistical analyses

IPD were analyzed using a one-stage approach. All statistical analyses were conducted with $\alpha = 0.05$ using R Studio software version 1.1.463 (R Studio, Inc., Boston, MA). Multilevel modeling was performed using lmer function in lme4 package to test the moderating roles of EF condition and pre-test performance on the effects of acute aerobic exercise on cognitive performance. The following multilevel models predicting the pre-post changes in cognitive performance were separately run for RT and accuracy:

Crude model:

Change in performance ~ Session + (1 | Participants) + (1 + Session | Study) + (1 + Session | EF domain)

Change in performance ~ EF condition + (1 | Participants) + (1 + EF condition | Study) + (1 + EF condition | EF domain)

Change in performance ~ Pre-test performance + I(Pre-test performance ^2) + (1 | Participants) + (1 + Pre-test performance + I(Pre-test performance ^2) | Study) + (1 + Pre-test performance + I(Pre-test performance ^2) | EF domain)

Model 1:

Change in performance ~ Session + EF condition + Pre-test performance + I(Pre-test performance ^2) + (1 | Participants) + (1 + Session + EF *condition + Pre-test performance + I(Pre-test performance ^2) | Study) + (1 + Session + EF condition + Pre-test performance + I(Pre-test performance ^2) | EF domain)*

Model 2:

Change in performance ~ Model 1 + Session:EF condition

Model 3:

Change in performance ~ Model 1 + Session:Pre-test performance

Model 4:

Change in performance ~ Model 3 + Session:I(Pre-test performance ^2)

Model 5:

Change in performance ~ Model 4 + Session:EF condition

Model fit was evaluated using the Akaike's Information Criterion (AIC) and χ^2 difference test. To avoid the failure of model convergence, non-significant random slope was excluded by automatic backward elimination using the step function. The session was coded as control = 0 and exercise = 1. The EF condition was coded as lower-EF condition = 0 and higher-EF condition = 1. Based on the purpose of the present study, post-hoc analyses were performed only when interactions involving session were significant. Outliers (> 3 *SD*) were removed from each of the data sets, and all behavioral measures were converted to z-scores within each study before statistical analyses to eliminate the influence of different units of measurement used in each study (e.g., sec versus msec, number of correct responses versus percent of correct responses). All coefficients reported in the results are unstandardized.

3. Results

3.1. Study characteristics

The literature review yielded 18 studies (19 experiments; one study included two different experiments, Soga et al., 2015) that were found to be eligible for the current meta-analysis. Their characteristics are summarized in Table 1. IPD were checked for integrity by reviewing completeness. No important issues were identified in checking IPD. Results for risk of bias assessments in included studies are provided in

Table 1
Summary of the included studies examining the effects of acute aerobic exercise on cognitive performance.

Author	Participants' characteristics	Exercise intervention	Cognitive task	Domain
Alves et al., 2012	42 female adults aged 52 years	30 min walking/jogging at 50 − 60% HRR	Stroop Trail-making	Inhibition Flexibility
Alves et al., 2014	22 adults (9 males, 13 females) aged 54 years	3 min warm-up at 60 % HRR, 10 × 1 min of HIIT cycling at 80 % HRR followed by active recovery at 60 % HRR	Stroop	Inhibition
Beyer et al., 2017	10 adults (6 males, 6 females) aged 24 years	5 min warm-up, 40 min cycling at 40 − 50% VO_2R	Flanker	Inhibition
Byun et al., 2014	25 adults (13 males, 12 females) aged 21 years	10 min cycling at mean HR = 107 bpm and mean RPE = 11	Stroop	Inhibition
Cooper et al., 2016	44 children (21 males, 23 females) aged 13 years	10 × 10 s HIIT sprints followed by 50 s active recovery walking	Stroop	Inhibition
Drollette et al., 2012	36 children (16 males, 20 females) aged 10 years	Walking/jogging at 60 % HR_{max} (mean duration = 20 min)	Flanker	Inhibition
			N-back	Working memory
Fiorelli et al., 2019	12 adults with Parkinson's disease (6 males, 6 females) aged 67 years	4 min warm-up at RPE = 9–11, 26 min cycling at RPE = 11–13. mean HR = 107 bpm, mean RPE = 11	Trail-making	Flexibility
Ludyga et al., 2017	18 healthy children (10 males, 8 females) aged 14 years 16 children with ADHD (11 males, 5 females) aged 13 years	20 min cycling at 65 − 70% HR_{max}	Flanker	Inhibition
McGowan et al., 2019	58 adults (26 males, 32 females) aged 19 years	20 min of exercise on a motor-driven treadmill at 54 % HRR and OMNI RPE = 3	Flanker	Inhibition
Pontifex et al., 2009	21 adults (12 males, 9 females) aged 20 years	30 min walking/jogging at 60–70 % VO_{2max}	Sternberg	Working memory
Salerno et al., 2019	27 female breast cancer survivors aged 49 years	30 min walking/jogging at 40 − 60% HR_{max}	Spatial Working memory	Working memory
Salerno et al., 2020	48 females with breast cancer aged 56 years	Either 10, 20, or 30 min walking at mean HR = 100 bpm and mean RPE = 9	Flanker	Inhibition
			Spatial Working memory Task switching	Working memory Flexibility
Sandroff et al., 2015	24 adults (1 male, 23 females) aged 44 years	5 min warm-up, 20 min walking/jogging at 60 % HRR, 5 min cool-down	Flanker	Inhibition
Sandroff et al., 2016	24 adults (1 male, 23 females) aged 40 years	5 min warm-up, 20 min walking/jogging at 50 % HRR, 5 min cool-down	Flanker	Inhibition
Soga et al., 2015 Experiment 1	28 children (24 males, 4 females) aged 16 years	5 min warm-up, walking/jogging at 60 % HR_{max} (mean duration = 13 min)	Flanker	Inhibition
			N-back	Working memory
Soga et al., 2015 Experiment 2	27 children (18 males, 9 females) aged 16 years	5 min warm-up, walking/jogging at 70 % HR_{max} (mean duration = 14 min)	Flanker	Inhibition
			N-back	Working memory
Weng et al., 2015	26 adults (12 males, 14 females) aged 25 years	5 min warm-up, 30 min cycling at 65 % HR_{max}, 5 min cool-down	Flanker	Inhibition
			N-back	Working memory
Yamazaki et al., 2018	30 adults (19 males, 11 females) aged 22 years	10 min cycling at 50 % VO_{2peak}	*N*-back	Working memory
Yanagisawa et al., 2010	20 adults (17 males, 3 females) aged 22 years	10 min cycling at 50 % VO_{2peak}	Stroop	Inhibition

Note: age are presented as mean; ADHD = attention deficit hyperactivity disorder; HIIT = high-intensity interval training; HR_{max} = maximum heart rate; HRR = heart rate reserve; RPE = rate of perceived exertion; VO_{2max} = maximum oxygen uptake; VO_{2peak} = peak oxygen uptake; VO_2R = oxygen uptake reserve.

Table 2
Results of multilevel multiple regression analyses predicting the pre-post change in reaction time.

	Crude model									Model 1			Model 2			Model 3			Model 4			Model 5		
Fixed effect	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
Intercept	−0.17	0.07	.06	−0.17	0.06	.03	−0.20	0.06	.02	−0.22	0.06	.01	−0.24	0.06	.006	−0.22	0.06	.009	−0.24	0.06	.007	−0.25	0.06	.005
Session	−0.13	0.05	.02							−0.13	0.04	.009	−0.09	0.05	.06	−0.13	0.04	.009	−0.10	0.05	.04	−0.08	0.05	.14
EF condition				−0.13	0.05	.03				0.16	0.02	<.001	0.20	0.03	<.001	0.16	0.02	<.001	0.16	0.02	<.001	0.19	0.03	<.001
Pre-test RT							−0.24	0.03	<.001	−0.31	0.03	<.001	−0.31	0.03	<.001	−0.28	0.03	<.001	−0.29	0.03	<.001	−0.30	0.03	<.001
I(Pre-test RTˆ2)							−0.01	0.01	.18	0.00	0.01	.70	0.00	0.01	.69	0.00	0.01	.75	0.01	0.01	.34	0.01	0.01	.31
Session:EF condition													−0.08	0.03	.01							−0.05	0.04	.19
Session:Pre-test RT																−0.05	0.02	.002	−0.03	0.02	.09	−0.02	0.02	.42
Session:I(Pre-test RTˆ2)																			−0.03	0.01	.02	−0.04	0.01	.01
Random effect	Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*	
Participants																								
Intercept	0.03	0.18		0.03	0.18		0.05	0.21		0.06	0.24		0.06	0.24		0.06	0.24		0.06	0.24		0.06	0.24	
Study																								
Intercept	0.01	0.10		0.02	0.14		0.02	0.14		0.01	0.11		0.01	0.11		0.01	0.11		0.01	0.11		0.01	0.11	
Session	0.03	0.18								0.03	0.18		0.03	0.18		0.03	0.18		0.03	0.18		0.03	0.18	
EF condition				0.01	0.11					NS			NS			NS			NS			NS		
Pre-test RT							0.003	0.06		0.004	0.06		0.004	0.06		0.003	0.06		0.004	0.06		0.004	0.06	
I(Pre-test RTˆ2)							<.001	0.03		<.001	0.03		<.001	0.03		0.001	0.03		0.001	0.03		0.001	0.03	
EF domain																								
Intercept	0.01	0.10		0.006	0.08		0.007	0.09		0.007	0.08		0.007	0.08		0.007	0.08		0.007	0.08		0.007	0.08	
Session	NS									NS			NS			NS			NS			NS		
EF condition				0.003	0.06					NS			NS			NS			NS			NS		
Pre-test RT							0.002	0.04		0.002	0.04		0.002	0.04		0.002	0.04		0.002	0.04		0.002	0.04	
I(Pre-test RTˆ2)							NS			NS			NS			NS			NS			NS		
Residual	0.24	0.49		0.24	0.49		0.002	0.04		0.18	0.42		0.18	0.42		0.18	0.42		0.18	0.42		0.18	0.42	
AIC										3750			3746			3743			3739			3740		
χ^2													6.09[a]			9.18[a]			5.58[b]			1.73[c]		
p													.01			.002			.02			.19		

Note: EF = executive function; NS = not significant; RT = reaction time; SD = standard deviation; SE = standard error; [a] versus Model 1; [b] = versus Model 3; [c] versus Model 4.

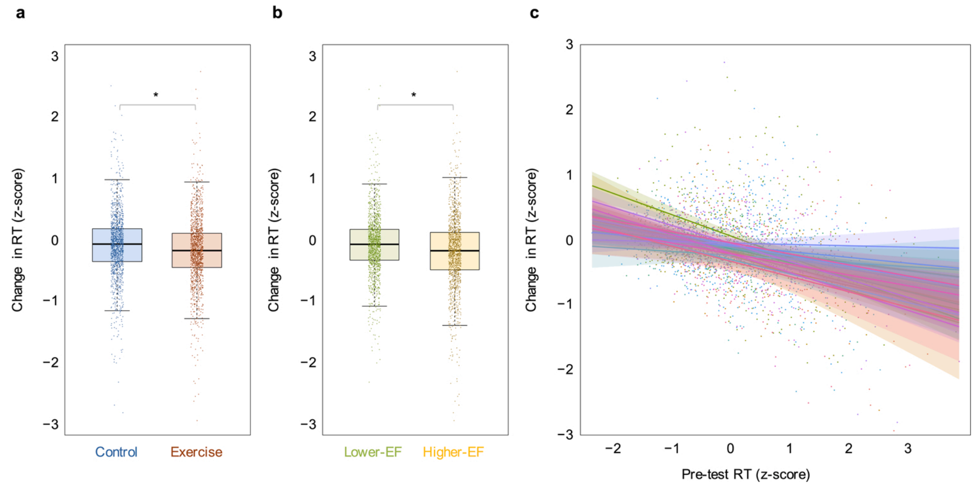

Fig. 2. Results of reaction time in the crude model of the multilevel modeling. a. Pre-post changes in RT illustrating a main effect of session. * $p < .05$. b. Pre-post changes in RT illustrating a main effect of EF condition. * $p < .05$. c. Relationship between pre-test RTs and pre-post changes in RT in each study ($n = 19$) illustrating a significant main effect of pre-test RT. Regression lines are shown with 95 % confidence bands (shaded areas).

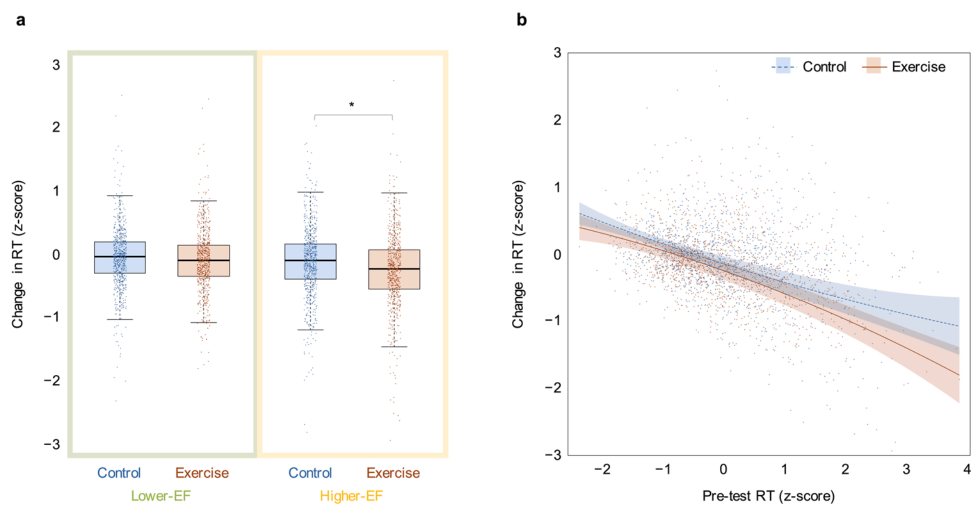

Fig. 3. Results of reaction time in models 2 and 4 of the multilevel modeling. a. Pre-post changes in RT illustrating a significant session × EF condition interaction. * $p < .05$. b. Relationship between pre-test RTs and pre-post changes in RT illustrating a significant session × pre-test RT interaction. Regression lines are shown with 95 % confidence bands (shaded areas).

Supplementary Table 2. The details of the data used in each study are summarized in Supplementary Table 3. The results of automatic backward elimination are summarized in Supplementary Tables 4–6.

3.2. Reaction time

The results of the multilevel modeling are summarized in Table 2. The multilevel modeling included 2796 observed cases from 505 participants derived from 19 studies. Crude models revealed significant main effects of session ($B = -0.13$, $p = .02$), EF condition ($B = -0.13$, $p = .03$), and pre-test RT ($B = -0.24$, $p < .001$), while the main effect of I (pre-test RT^2) was not significant ($B = -0.01$, $p = .18$). These results indicate that acute exercise improved RT (Fig. 2a), and that a greater reduction in RT was observed in the higher-EF condition (Fig. 2b) and in participants with longer pre-test RT irrespective of session (Fig. 2c).

Model 1 revealed significant main effects of session ($B = -0.13$, $p = .009$), EF condition ($B = 0.16$, $p < .001$), and pre-test RT ($B = -0.31$, $p < .001$), while the main effect of I(pre-test RT^2) was not significant ($B = -0.004$, $p = .70$). Model 2 revealed a significant two-way interaction between session and EF condition ($B = -0.08$, $p = .01$), indicating that the beneficial effect of acute exercise on RT was greater in the higher-EF condition (lower-EF: $B = -0.09$, $SE = 0.05$, $p = .06$, higher-EF: $B = -0.17$, $SE = 0.05$, $p < .001$) (Fig. 3a). Model 3 revealed a significant two-way interaction between session and pre-test RT ($B = -0.06$, $p = .002$), indicating that the beneficial effect of acute exercise on RT was greater in participants with longer pre-test RT. In addition, Model 4 revealed a significant two-way interaction between session and I(pre-test RT^2) ($B = -0.03$, $p = .02$), indicating that the quadratic nature of the

Table 3
Results of multilevel multiple regression analyses predicting the pre-post change in accuracy.

	Crude model									Model 1			Model 2			Model 3			Model 4			Model 5		
Fixed effect	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
Intercept	0.01	0.05	.82	0.05	0.05	.32	0.05	0.04	.20	0.20	0.04	.005	0.20	0.05	.004	0.19	0.04	.006	0.20	0.05	.005	0.20	0.05	.004
Session	0.08	0.04	.09							0.07	0.02	<.001	0.06	0.03	.05	0.08	0.02	<.001	0.07	0.03	.006	0.07	0.04	.05
EF condition				−0.01	0.03	.84				−0.28	0.07	.04	−0.29	0.07	.03	−0.28	0.07	.04	−0.28	0.07	.04	−0.28	0.07	.03
Pre-test accuracy							−0.43	0.05	<.001	−0.57	0.04	<.001	−0.57	0.04	<.001	−0.54	0.05	<.001	−0.54	0.05	<.001	−0.54	0.05	<.001
I(Pre-test accuracy^2)							0.05	0.02	.04	0.01	0.02	.56	0.01	0.02	.57	0.01	0.02	.57	0.00	0.02	.83	0.00	0.02	.83
Session:EF condition													0.03	0.04	.42							0.00	0.05	.98
Session:Pre-test accuracy																−0.07	0.03	.02	−0.05	0.04	.13	−0.05	0.04	.17
Session:I(Pre-test accuracy^2)																			0.01	0.02	.57	0.01	0.02	.57
Random effect	Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*	
Participants																								
Intercept	0.02	0.14		0.02	0.14		0.03	0.18		0.05	0.22		0.05	0.22		0.05	0.22		0.05	0.22		0.05	0.22	
Study																								
Intercept	0.006	0.08		0.005	0.07		0.006	0.08		0.004	0.06		0.004	0.06		0.003	0.06		0.003	0.06		0.003	0.06	
Session	0.02	0.13								NS			NS			NS			NS			NS		
EF condition				NS						NS			NS			NS			NS			NS		
Pre-test accuracy							0.03	0.17		0.02	0.14		0.02	0.14		0.02	0.14		0.02	0.14		0.02	0.14	
I(Pre-test accuracy^2)							0.004	0.06		0.004	0.06		0.004	0.06		0.003	0.06		0.003	0.06		0.003	0.06	
EF domain										NS			NS			NS			NS			NS		
Intercept	0.005	0.07		0.005	0.07		0.002	0.04		0.003	0.05		0.003	0.06		0.003	0.06		0.003	0.06		0.003	0.06	
Session	NS									NS			NS			NS			NS			NS		
EF condition				NS						0.01	0.11		0.01	0.11		0.01	0.11		0.01	0.11		0.01	0.11	
Pre-test accuracy							NS			NS			NS			NS			NS			NS		
I(Pre-test accuracy^2)							NS			NS			NS			NS			NS			NS		
Residual	0.45	0.67		0.46	0.68		0.31	0.56		0.28	0.53		0.28	0.53		0.28	0.53		0.28	0.53		0.28	0.53	
AIC										4435			4436			4431			4433			4433		
χ^2													0.66[a]			5.48[a]			0.33[b]			< .001[c]		
p													.42			.02			.57			.98		

Note: EF = executive function; NS = not significant; SD = standard deviation; SE = standard error; [a] versus Model 1; [b] = versus Model 3; [c] versus Model 4.

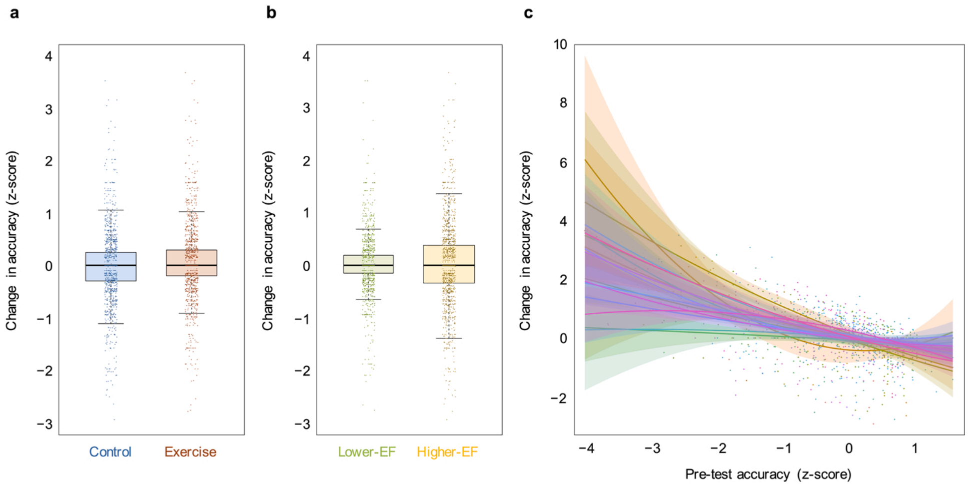

Fig. 4. Results of accuracy in the crude model of the multilevel modeling. a. Pre-post changes in accuracy illustrating a non-significant main effect of session. b. Pre-post changes in accuracy illustrating a non-significant main effect of EF condition. c. Relationship between pre-test accuracy and pre-post changes in accuracy in each study (n = 16) illustrating a significant main effect of pre-test accuracy and I(pre-test accuracy^2). Regression lines are shown with 95 % confidence bands (shaded areas).

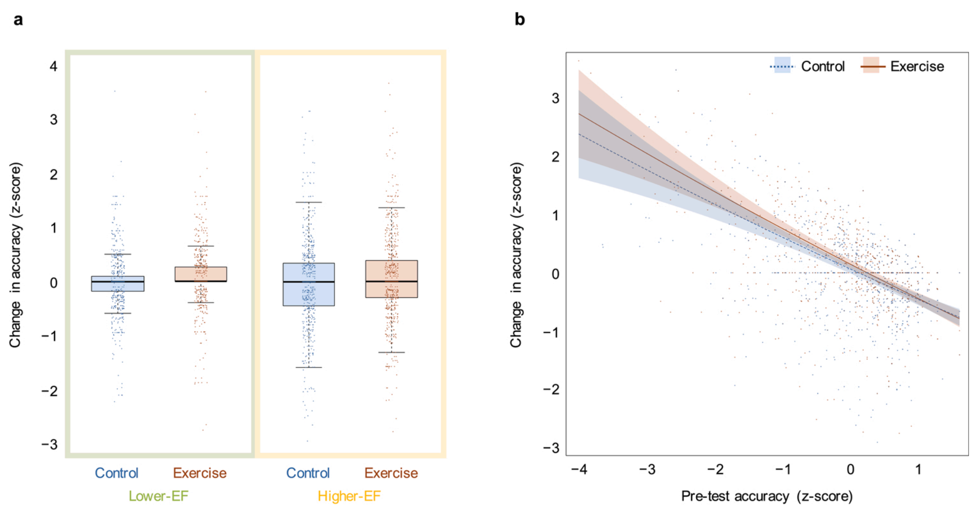

Fig. 5. Results of accuracy in models 2 and 3 of the multilevel modeling. a. Pre-post changes in accuracy illustrating a non-significant session × EF condition interaction. b. Relationship between pre-test accuracy and pre-post changes in accuracy illustrating a significant session × pre-test accuracy interaction. Regression lines are shown with 95 % confidence bands (shaded areas).

relationship between pre-test RT and the pre-post change in RT (Fig. 3b).

In Model 5, a two-way interaction between session and I(pre-test RT^2) remained significant (B = −0.04, p = .01), while the two-way interaction between session and EF condition was not significant (B = −0.05, p = .19). This final model indicates that the observed larger beneficial effect of acute exercise in the higher-EF condition in Model 2 (Fig. 3a) was reduced after adjusting for the interaction between session and pre-test RT.

3.3. Accuracy

The results of the multilevel modeling are summarized in Table 3. The multilevel modeling included 2596 observed cases from 455 participants derived from 16 studies. Crude models revealed no significant main effects of session (B = 0.08, p = .09) and EF condition (B = −0.005, p = .84), while the main effects of pre-test accuracy (B = −0.43, p < .001) and I(pre-test accuracy^2) (B = 0.05, p = .04) were significant. These results indicate that acute exercise and EF condition did not affect change in accuracy (Fig. 4a and b), and an increase in accuracy was greater in participants with lower pre-test accuracy (Fig. 4c).

Model 1 revealed significant main effects of session (B = 0.07, p < .001), EF condition (B = −0.28, p = .04), and pre-test accuracy (B = −0.57, p < .001), while the main effect of I(pre-test RT^2) was not significant (B = 0.01, p = .56). Model 2 revealed no significant two-way interaction between session and EF condition (B = 0.03, p = .42), indicating that the effects of acute exercise on accuracy did not statistically differ between EF conditions (Fig. 5a). Model 3 revealed a significant two-way interaction between session and pre-test accuracy (B = −0.07, p = .02), indicating that the beneficial effect of acute exercise on accuracy was greater in participants with lower pre-test accuracy (Fig. 5b). Model 4 did not show significant two-way interaction between

Table 4
Results of multilevel multiple regression analyses predicting the pre-post change in EF difference score of reaction time.

	Crude model						Model 1			Model 2			Model 3		
Fixed effect	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
Intercept	−0.09	0.05	.14	0.27	0.08	.03	0.31	0.09	.02	0.29	0.08	.02	0.30	0.09	.03
Session	−0.09	0.03	.005				−0.07	0.03	.003	−0.02	0.04	.68	−0.06	0.05	.19
Pre-test difference score				−0.50	0.08	.002	−0.50	0.08	.002	−0.48	0.07	<.001	−0.53	0.09	<.001
I(Pre-test difference score^2)				0.03	0.02	.08	0.03	0.02	.08	0.03	0.02	.04	0.06	0.02	.01
Session:Pre-test difference score										−0.06	0.04	.08	0.06	0.08	.43
Session:I(Pre-test difference score^2)													−0.05	0.03	.08
Random effect	Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*		Variance	*SD*	
Participants															
Intercept	NS			0.01	0.12		0.01	0.12		0.01	0.11		0.01	0.12	
Study															
Intercept	0.01	0.12		0.02	0.14		0.02	0.14		0.01	0.12		0.02	0.14	
Session	NS														
Pre-test difference score				NS			NS			NS			NS		
I(Pre-test difference score^2)				0.0009	0.03		0.0009	0.03		NS			0.0006	0.02	
EF domain															
Intercept	0.004	0.06		0.01	0.12		0.02	0.12		0.01	0.11		0.02	0.13	
Session	NS						NS			NS			NS		
Pre-test difference score				0.01	0.11		0.01	0.11		0.007	0.08		0.01	0.12	
I(Pre-test difference score^2)				NS			NS			NS			NS		
Residual	0.33	0.57		0.22	0.47		0.22	0.47		0.22	0.47		0.22	0.47	
AIC							2000			2000			1998		
χ^2										1.96[a]			5.75[b]		
p										.17			.06		

Note: EF = executive function; NS = not significant; SD = standard deviation; SE = standard error; [a] versus Model 1; [b] = versus Model 2.

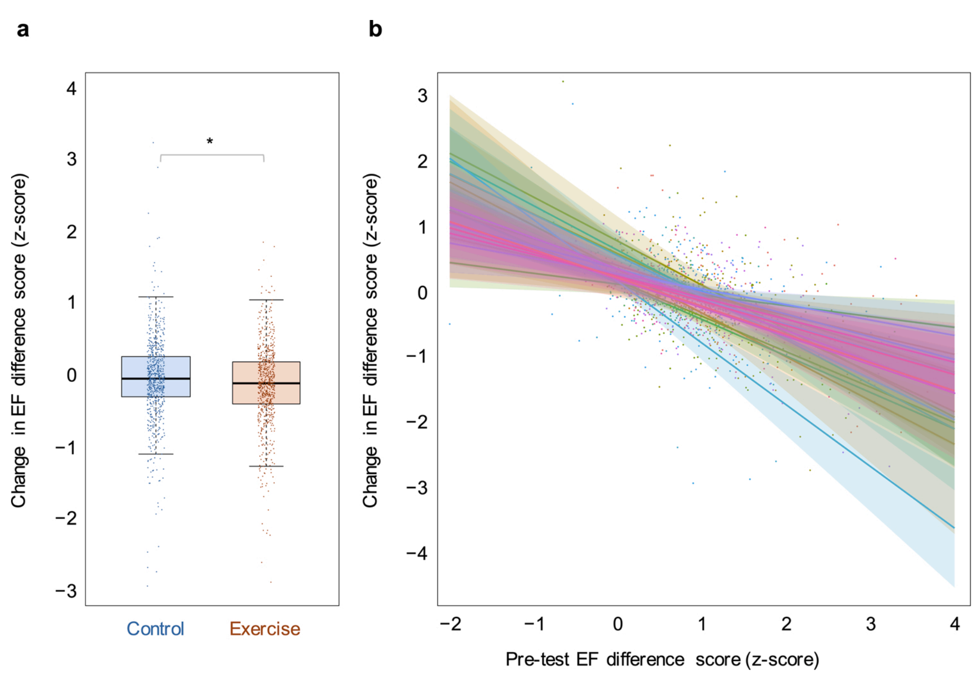

Fig. 6. Results of EF difference score in the crude model of the multilevel modeling. a. Pre-post changes in EF difference score illustrating a main effect of session. * $p < .05$. b. Relationship between pre-test EF difference scores and pre-post changes in EF difference score in each study ($n = 19$) illustrating a significant main effect of pre-test EF difference score. Regression lines are shown with 95 % confidence bands (shaded areas).

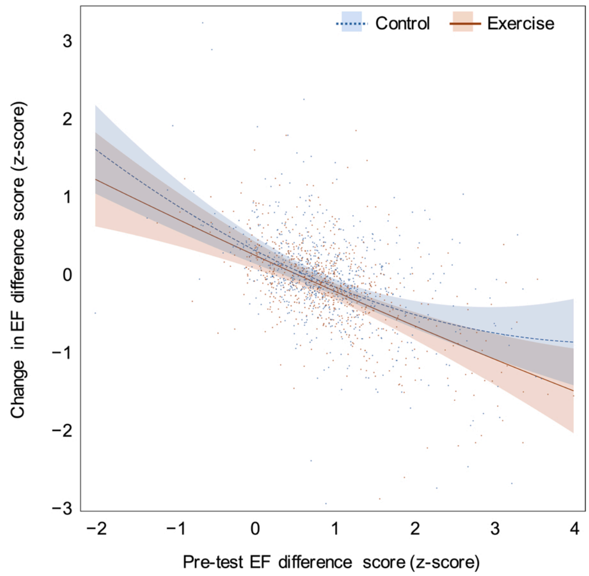

Fig. 7. Result of EF difference score in model 3 of the multilevel modeling. Relationship between pre-test EF difference scores and pre-post changes in EF difference score illustrating marginally significant session × pre-test EF difference score and session × I(pre-test EF difference score^2) interactions. Regression lines are shown with 95 % confidence bands (shaded areas).

session and I(pre-test RT^2) (B = 0.01, p = .57). Model 5 did not show any significant two-way interactions (B = −0.05 to 0.01, p = .17–.98).

3.4. EF difference score

Given that the main analysis indicated that longer pre-test RT was associated with greater benefits from acute aerobic exercise, the disproportionately greater effects on a higher-EF condition would be predicted if the difference in pre-test RT between lower-EF and higher-EF conditions (hereafter referred to as "EF difference score") were sufficiently large. Based on this prediction, we performed multilevel modeling predicting the change in the EF difference score of RT following the analytical procedure of the above main analyses.

The results of the multilevel modeling are summarized in Table 4. The multilevel modeling included 1398 observed cases from 505 participants derived from 19 studies. Crude models revealed significant main effects of session (B = −0.09, p = .005) and pre-test EF difference score (B = −0.50, p = .002), while the main effect of I(pre-test EF difference score ^2) was not significant (B = 0.03, p = .08). These results indicate that acute exercise reduced the EF difference score (Fig. 6a), and that a greater reduction in EF difference score was observed in participants with larger EF difference score at pre-test irrespective of session (Fig. 6b).

Model 1 revealed significant main effects of session (B = −0.07, p = .003) and pre-test EF difference score (B = −0.50, p = .002), while the main effect of I(pre-test EF difference score ^2) was not significant (B = 0.03, p = .08). Note that the observed session main effect means the same thing as the two-way interaction between session and EF condition of the above RT analysis. The two-way interactions between session and pre-test EF difference score in model 2 and between session and I(pre-test EF difference score ^2) in model 3 did not reach statistical significant ($p \geq$ .05). These results suggest that the effects of acute aerobic exercise on EF difference score did not statistically differ based on the pre-test EF difference score (Fig. 7), which does not support our post-hoc prediction.

4. Discussion

4.1. Main findings

The main findings of the present IPD meta-analysis revealed that cognitive performance improved following an acute bout of aerobic exercise. Nonetheless, it should be noted that more than one-third of the included studies failed to find beneficial effects of acute aerobic exercise on EFs. To explore possible sources of heterogeneity among the previous studies, the present IPD meta-analysis further examined the moderating roles of EF condition and pre-test performance on the effects of acute aerobic exercise on cognitive performance. The RT findings showed that the beneficial effects of acute aerobic exercise were greater in the higher-EF, relative to the lower-EF, condition, when pre-test performance was not considered. However, acute aerobic exercise offers general benefits to RT performance irrespective of EF condition, when pre-test performance is appropriately controlled. The accuracy findings only showed the moderating role of pre-test performance, but not of EF condition, on the effects of acute exercise. Stated differently, although the beneficial effects were greater in participants with lower pre-test accuracy, the effects of acute exercise on accuracy did not statistically differ between EF conditions. Taken together, acute aerobic exercise seems to have general rather than EF-specific benefits on cognitive performance. Additional post-hoc analysis using the EF difference score of RT supports this finding, indicating that the disproportionately greater effects on a higher-EF condition would not be observed even when pre-test EF difference score is large.

The following two implications should be highlighted from the present findings. The present results demonstrated that pre-test performance strongly moderated the effects of acute exercise on cognitive performance. Accordingly, researchers are encouraged to consider pre-test performance in acute exercise studies, via manipulating task difficulty and/or by controlling for pre-test performance in statistical analyses. Second, in this context, a typical between-participants design, which does not incorporate inter-individual differences in pre-test performance, is generally considered unsuitable for acute exercise studies. Although the study design should be primarily selected based on the study purpose, in acute exercise studies, researchers are encouraged to employ a within-participants design, whenever possible.

4.2. Limitations

The strength of the present study lies in using the IPD approach. The IPD meta-analysis, which allows the comparison of pre-test performance within a study, is considered a suitable approach to examine the moderating roles of EF condition and pre-test performance. Nonetheless, some limitations should be acknowledged. Given that pre-test performance should be lower in the higher-EF relative to the lower-EF condition, EF condition and pre-test performance are inseparable. Additionally, a smaller but non-zero amount of EFs are required even in the lower-EF condition. Thus, the present findings do not necessarily disagree with acute exercise having beneficial effects on prefrontal dependent EFs. Although several neuroimaging studies using functional near-infrared spectroscopy (Byun et al., 2014; Yanagisawa et al., 2010) have examined the effects of acute exercise on brain activity, these studies have mainly focused on the prefrontal cortex following the current research trend. Based on the present findings showing generalized beneficial effects, other brain regions and networks may also be influenced by acute exercise. Further neuroimaging studies using a brain network approach are needed. Next, given that the present IPD meta-analysis focused on the moderating role of pre-test performance, only studies using the most rigorous study design (i.e., within-participants crossover pretest posttest comparison design) were included in the analyses. Thus, the number of studies included in the present IPD meta-analysis was relatively small. More studies using the most rigorous experimental designs are needed not only to further characterize the effects of acute exercise relative to protocols (e.g., exercise intervention, cognitive measures) and participants' characteristics (e.g., age, sex, fitness level), but also to clarify whether the current findings are generalizable to other populations that do not match the present samples (e.g., preschoolers).

4.3. Conclusions

The present IPD meta-analysis provides novel evidence regarding the moderating roles of EF condition and pre-test performance on the effects of acute aerobic exercise on cognitive performance. In conclusion, the beneficial effects of acute aerobic exercise appear to be general irrespective of EF conditions, and strongly moderated by pre-test performance. Our findings will hopefully provide a useful path for future research and contribute to the further development of research aimed at the benefits of acute exercise for brain and cognition.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.neubiorev.2021.06.026.

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