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SYSTEMATIC REVIEW

Effects of Prior Cognitive Exertion on Physical Performance: A Systematic Review and Meta-analysis

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Abstract

Background An emerging body of the literature in the past two decades has generally shown that prior cognitive exertion is associated with a subsequent decline in physical performance. Two parallel, but overlapping, bodies of literature (i.e., ego depletion, mental fatigue) have examined this question. However, research to date has not merged these separate lines of inquiry to assess the overall magnitude of this effect.

Objective The present work reports the results of a comprehensive systematic review and meta-analysis examining carryover effects of cognitive exertion on physical performance.

Methods A systematic search of MEDLINE, PsycINFO, and SPORTDiscus was conducted. Only randomized controlled trials involving healthy humans, a central executive task requiring cognitive exertion, an easier cognitive comparison task, and a physical performance task were included.

Results A total of 73 studies provided 91 comparisons with 2581 participants. Random effects meta-analysis showed a significant small-to-medium negative effect of prior cognitive exertion on physical performance ($g = -0.38$ [95% CI -0.46, -0.31]). Subgroup analyses showed that cognitive tasks lasting < 30-min ($g = -0.45$) and ≥ 30-min ($g = -0.30$) have similar significant negative effects on subsequent physical performance. Prior cognitive exertion significantly impairs isometric resistance ($g = -0.57$), motor ($g = -0.57$), dynamic resistance ($g = -0.51$), and aerobic performance ($g = -0.26$), but the effects on maximal anaerobic performance are trivial and non-significant ($g = 0.10$). Studies employing between-subject designs showed a medium negative effect ($g = -0.65$), whereas within-subject designs had a small negative effect ($g = -0.28$).

Conclusion Findings demonstrate that cognitive exertion has a negative effect on subsequent physical performance that is not due to chance and suggest that previous meta-analysis results may have underestimated the overall effect.

1 Introduction

Over the past two decades, a growing body of literature has examined the carryover effects of performing cognitive tasks on subsequent physical performance. Several recent efforts to synthesize the literature both narratively [1–4] and quantitatively [5] have shown negative carryover effects whereby performing cognitive tasks leads to subsequent decreases in physical performance across a broad range of aerobic, resistance (isometric or dynamic) and sport-specific motor tasks. However, there are several shortcomings of these reviews that limit our current understanding of this relationship. Perhaps the biggest limitation is that existing reviews have drawn upon studies extracted from the mental fatigue literature and excluded studies from the self-control/ego-depletion literature, despite substantial methodological similarities between the two. Therefore, to more fully describe and interpret the magnitude and direction of this effect as well as moderators of the prior cognitive exertion–physical performance relationship, a more comprehensive synthesis and analysis that unites the mental fatigue and ego-depletion literatures is required.

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Key Points

Prior cognitive exertion has a significant small-to-medium-sized negative effect on subsequent physical performance that is not due to random error.

Prior cognitive exertion significantly impairs isometric resistance, dynamic resistance, motor, and aerobic performance, but not maximal anaerobic performance.

Cognitive manipulation duration does not moderate the prior cognitive exertion–physical performance relationship.

The first modern[1] studies to investigate whether prior cognitive exertion influences physical performance were conducted by researchers in the area of self-control or ego depletion from the perspective of the resource or strength model of self-control [6–8]. Self-control is defined as one's ability to override and alter unwanted behavioral, emotional and cognitive responses to align with standards or goals [9]. The term "ego depletion" refers to a phenomenon in which people have an increased susceptibility to self-control failure due to prior engagement in a task requiring self-control [9]. The resource model proposes that all acts of self-control whether they be cognitive, emotional or behavioral are dependent on an undifferentiated resource and when the resource is depleted or fatigued by exerting self-control on one task, fewer resources are available for subsequent tasks and performance on those latter tasks is negatively affected [8, 10]. The self-control/ego-depletion literature is composed of hundreds of studies investigating carryover effects from one task to another using sequential combinations of tasks requiring cognitive, emotional, and behavioral control [11].

An early meta-analysis of the self-control literature revealed a significant medium-sized negative ego-depletion effect ($d = -0.62$; [11]). However, critical concerns over whether an ego-depletion effect actually exists were brought forward when meta-analysis using alternative techniques [12] and a registered replication project involving consecutive cognitive tasks [13] failed to show statistically significant effects. Other researchers [14–17] were quick to respond to this evidence by pointing out limitations to the procedures and techniques used in the studies that showed null effects. Results of an updated meta-analysis also suggest that Hagger et al.'s [11] analysis produced a biased estimate of the ego-depletion effect and that it is more likely in the small effect size range ($g = -0.38$; Dang [17]).

Although there continues to be considerable controversy about the legitimacy of an ego-depletion effect, it is important to recognize that within that larger body of literature there are numerous studies that have focused on the effects of tasks requiring cognitive self-control exertion on subsequent physically demanding tasks and, to date, only one narrative review has attempted to synthesize findings from those studies [1]. In his analysis, Englert [1] illustrated consistent evidence of ego-depletion effects across multiple sport and exercise contexts; however, the overall magnitude of this effect remains unknown. Therefore, quantifying the prior cognitive exertion–physical performance relationship will address a significant gap in the current knowledge and provide important insight regarding the direction and magnitude of ego-depletion effects in the context of physical activity.

Ego depletion refers to depletion of a resource brought on by exerting self-control. On the other hand, mental fatigue refers to a complex psychophysiological phenomenon that results in feelings of tiredness or lack of energy following exposure to tasks that require prolonged cognitive exertion [18]. In the past decade, a rapidly growing body of literature examining the effects of mental fatigue on physical performance has emerged. Akin to studies investigating ego depletion in sport or exercise contexts, studies from the mental fatigue literature have participants complete tasks that require cognitive exertion prior to performing a physically demanding task and compare that physical performance to one that was completed after a "control" task requiring less cognitive exertion.

There have been several recent efforts to synthesize the mental fatigue literature both narratively [2] and quantitatively [5]. In the most comprehensive review to date, McMorris and colleagues [5] conducted a meta-analysis, which demonstrated a small negative effect ($g = -0.26$[2]) of mental fatigue on physical performance. Those authors concluded: "…the very small T^2 result indicates that there was no real significant effect and that differences are due more to random error." (p. 105). However, a major caveat to this conclusion is the authors' use of strict inclusion criteria that disqualified all but one study that involved cognitive manipulations lasting < 30 min, which led them to consider the results of only 8 studies from what is a much more substantial literature. Further, they only offered information in their analyses regarding potential publication bias in the literature, but not risk of bias within the studies included, and

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[1] We acknowledge the seminal thinking and first research on the connection between mental fatigue and physical performance that was carried out by Angelo Mosso in 1906. However, given the extent of reporting in Mosso's writings, the data could not be included in the analysis.

[2] McMorris et al. [5] originally reported an effect size of $g = -0.27$ which has since been corrected.

did not consider variables that could moderate the overall effect.

Building on the findings of McMorris et al. [4], Pageaux and Lepers [19] conducted a review of the mental fatigue literature that examined carryover effects specific to different types of physical tasks (e.g., aerobic, resistance, maximal anaerobic, motor skills). Their findings revealed performance impairments for aerobic- and resistance-based tasks involving prolonged submaximal effort regulation as well as motor skill-based tasks. Conversely, performance of brief maximal anaerobic tasks were found to be unaffected by mental fatigue. While theirs was the first study to investigate moderators of the prior cognitive exertion–physical performance relationship, Pageaux and Lepers [19] did not use statistical techniques to quantify the magnitude of these effects. Further analyses to determine the extent to which performance in some contexts may be impaired to a greater or lesser level than in others may serve to provide exercise scientists, practitioners, athletes and exercisers with valuable information pertaining to pre-performance behaviors that may be important to avoid to optimize performance.

Reviews of each of the mental fatigue and ego-depletion literatures have yielded similar findings, yet there has been no attempt to integrate the two literatures despite strong similarities in study designs and methodologies. Indeed, studies from both areas have used the same tasks for the cognitive manipulations (e.g., Stroop task; Stroop [20]) and physical performance assessments (e.g., aerobic exercise) that, apart from being performed for different durations, have similar, if not identical, task demands. However, despite utilizing common cognitive tasks involving central executive processes such as response inhibition [21], one consistent difference between mental fatigue and ego-depletion studies is the duration of the cognitive manipulations [4]. That is, most mental fatigue studies utilize cognitive manipulations lasting ≥ 30 min, whereas ego-depletion studies typically use manipulations of shorter duration, with some as brief as 3 min and 40 s [22].

In their recent review, Van Cutsem et al. [4] argued the minimum task duration necessary to induce mental fatigue is 30 min, based on studies showing decrements in vigilance [23] and increases in mental fatigue [24] occurring around this time point, which was part of their rationale for limiting their review to studies with manipulations of that duration or longer. They also argued against including studies from the ego-depletion literature that used cognitive manipulations lasting < 30 min due to evidence discussed earlier that failed to show an ego-depletion effect in a multi-lab replication study in which the depletion task was reported to be more difficult, effortful and frustrating, but not more fatiguing [13]. However, this conclusion is errant for at least two reasons. First, it is based on results of a replication effort that did not involve a physical performance task. Second, it fails to recognize numerous ego-depletion studies that have documented significant increases in self-reported mental fatigue following brief cognitive manipulations (e.g., Bray et al. [25]; Brown and Bray [26, 27]; Graham and Bray [28]; Lubusko [29]; Muraven et al. [8]) which has led theorists to posit ego depletion is a form of mental fatigue [11, 30].

Previous research also indicates the extent of cognitive exertion or mental fatigue is task dependent as more demanding cognitive tasks can result in high levels of fatigue in a fraction of the time required by less difficult cognitive tasks. For instance, subjective ratings of mental fatigue reported at 2-min intervals during a highly demanding, 10-min Stroop task [27], were almost identical to subjective mental fatigue reported at 10-min intervals during a moderately demanding, 50-min continuous performance task [31]. In light of this evidence, it seems remiss to exclude studies from narrative or quantitative reviews simply on the basis of theoretical/empirical lineage or an arbitrarily determined cut-off of 30 min duration. On the contrary, analyzing studies that have used a range of durations for the cognitive manipulations could lend important insights to help determine dose–response relationships between prior cognitive exertion and physical performance. At the very least, given it has served as a base criterion for the three reviews of the mental fatigue literature carried out thus far, it seems worthwhile to investigate whether cognitive manipulation durations above and below the proposed 30 min cut-point criterion moderate the prior cognitive exertion–physical performance relationship.

In addition to examining cognitive task duration as a potential moderator, there is also an opportunity to gain important insights into the prior cognitive exertion–physical performance relation by investigating the potential moderating roles of other factors such as study design and publication status that have not been considered by previous reviews. Specifically, previous reviews have only included published studies [1–5], which potentially excludes studies that may not have been published due to null findings. Excluding unpublished research may have resulted in an overestimation of the direction and magnitude of the true effect. Moving forward, quantifying the effect sizes reported by published and unpublished studies will provide further insight regarding publication bias within this literature. Previous reviews in the mental fatigue literature have also only included studies employing within-subject designs. Although within-subject designs may have some advantages over between-group designs, excluding research based on design rather than assessing variability that may be attributable to design limits the knowledge that can be gleaned from the available data. Increasing the comprehensiveness of the analyses by including between-group studies serves to reduce selection bias as well as increase confidence in the reliability of observed effects.

In an attempt to integrate the findings from the mental fatigue and self-control/ego-depletion literatures as they relate to physical performance, we carried out a comprehensive review of research examining the effects of prior cognitive exertion on physical performance in healthy individuals. In addition to utilizing inclusion criteria to capture studies with cognitive manipulations lasting < 30 min, the differential effects of moderator variables including methodological design (i.e., between-groups versus within-subject), publication status (i.e., published versus unpublished) and the parameters of the physical task (i.e., aerobic, isometric resistance, dynamic resistance, maximal anaerobic or motor-based sport performance tasks) were assessed.

2 Methods

The current review followed the PRISMA guidelines for protocols and reporting items in systematic reviews and meta-analysis [32]. Items are reported using the PRISMA Checklist (see Electronic Supplementary Material 3: Table S1).

2.1 Eligibility Criteria

Inclusion criteria for this meta-analysis required: (a) to be performed on healthy humans; (b) a high cognitive exertion intervention involving (i) a central executive task requiring response inhibition, updating or shifting [21, 33], or (ii) a cognitive self-control task that required controlling attention, emotions, thoughts, and impulses, cognitive processing, or social processing, which have been argued to be dependent on executive functions [34]; (c) a comparison/control task involving (i) an easier/less demanding version of the intervention task or (ii) an alternative task that required low cognitive exertion demands; (d) an outcome task performed in normal (i.e., not deliberately manipulated by the researchers) environmental (e.g., temperature, altitude, humidity) conditions that provided an objective measure of physical performance in a sport/exercise context (i.e., aerobic, dynamic or isometric resistance, maximal anaerobic, or motor performance); (e) a randomized controlled trial design; (f) statistical information required to calculate effect sizes; and (g) to be reported in English. Missing data from eligible studies were requested by contacting the authors. Eligible studies were included in the qualitative analysis in cases where missing data were unable to be obtained.

2.2 Search Strategy and Study Selection

A systematic review of the literature was conducted in Medline, PsycINFO and SPORTDiscus from the earliest available date up to March 2018, which was later updated in September 2018. Search terms included combinations of mental* adj3 exertion or fatigu* or task*, cognitive* adj3 exertion or demand* or fatigu* or task* or control*, ego depletion, self-control, exercise, physical* or athletic* or exercise* or muscl* or neuromusc* or resist* or endurance* or isometric* or handgrip* or sport* adj3 endurance* or performance* or activity or effort or exert* or fatigu* or strength or training or task*.

The original search yielded 5106 records which was reduced to 4206 records after duplicates were removed. A team of six independent reviewers screened the titles and abstracts for inclusion criteria (two independent reviewers per study), resulting in 109 records for which the full texts were obtained. Two independent reviewers then read and assessed the full text articles for inclusion. Any disagreements were resolved through discussion and consensus. Reference lists of the 51 articles selected for inclusion as well as other reviews and meta-analyses on the subject were screened for any overlooked records, resulting in an additional 13 articles. One unpublished study was identified through the database search (Lubusko [29]) and the research team also contacted authors of included articles to request any unpublished reports that could potentially be included, which yielded 7 additional studies. An updated search using the original search strategy was conducted in September 2018 and provided an additional 8 articles to be included. Overall, a total of 79 articles that provided 98 comparisons were selected for inclusion in the qualitative review and 73 articles which provided 91 comparisons had sufficient statistical information to be included in the meta-analysis (see Fig. 1 for PRISMA flow diagram).

2.3 Data Extraction

Predetermined variables of interest were extracted from each included article into a data entry form within Microsoft Excel by one of the six independent reviewers. A second independent reviewer checked the data for errors. Relevant data extracted included: study design; sample characteristics (sample type and size); intervention and comparison/control task characteristics (task type and duration); and the physical performance outcome(s) measured as well as the results for each condition/group at each time point. In cases where the outcome measure data were only presented graphically, data were extracted using WebPlot-Digitizer [35].

A total of 91 effect sizes for physical performance outcomes were extracted from the 73 articles with sufficient statistical information. Physical performance outcomes were categorized into 5 groups (i.e., aerobic, dynamic resistance, isometric resistance, maximal anaerobic, and motor performance) based on the following criteria. Aerobic performance outcomes included (i) covering a given distance as quickly as possible, (ii) average velocity, average speed, average power output, covering as much distance or generating as much work as possible in a given time, and (iii) covering as

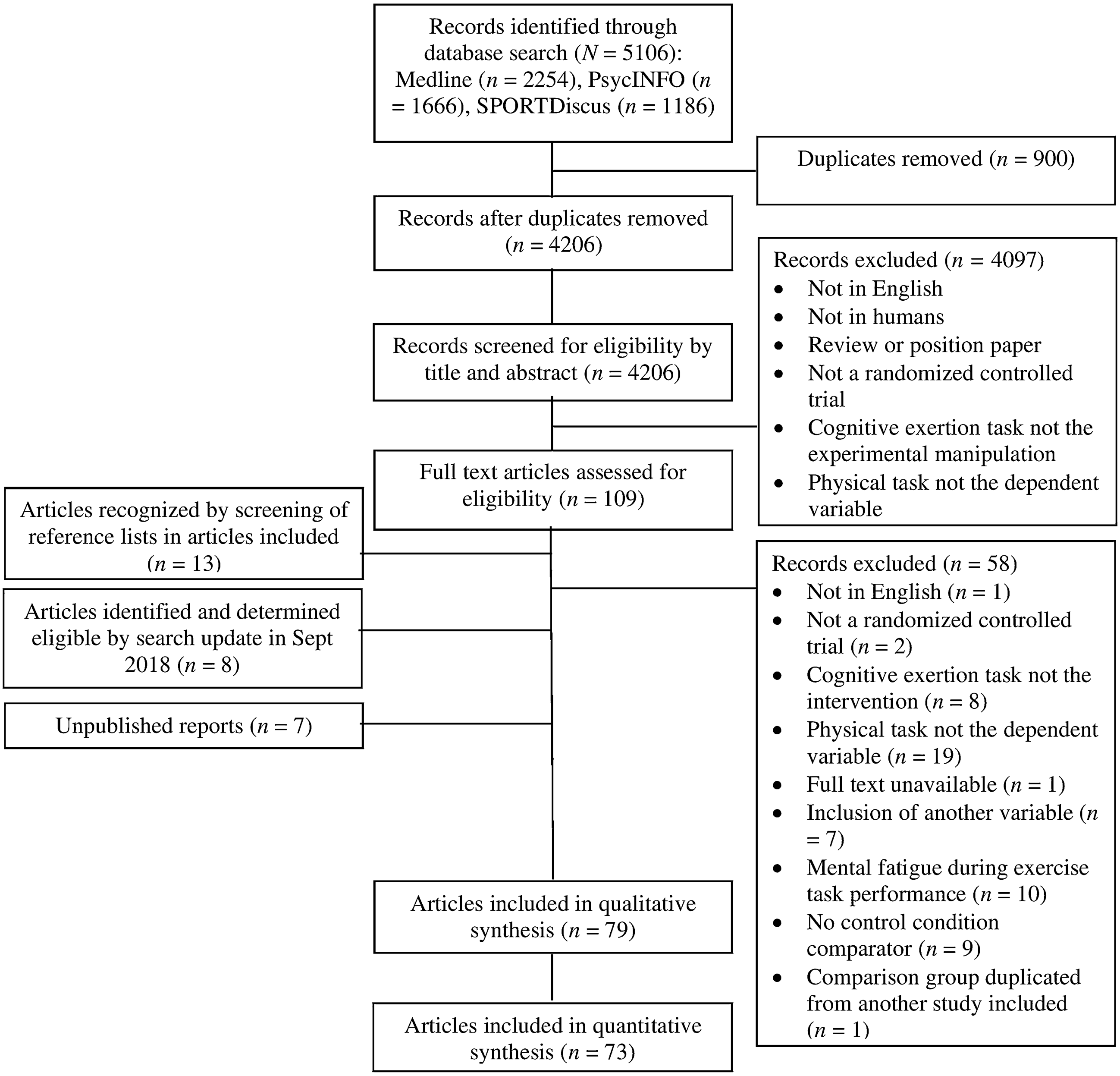

Fig. 1 PRISMA flowchart. 12 articles with multiple studies or district subsamples generated an additional 17 comparisons. Seven comparisons from six articles were excluded due to insufficient statistical information to compute effect sizes. 79 articles in the qualitative synthesis provided 98 independent comparisons. 73 articles in the quantitative synthesis provided 91 independent comparisons

much distance or generating as much work as possible until volitional exhaustion. Dynamic resistance performance outcomes included: (i) completing as many repetitions as possible or time on task in a given time, and (ii) completing as many repetitions until failure/volitional exhaustion. Isometric resistance performance outcomes included: (i) maintaining a given force production or posture to failure/volitional exhaustion. Maximal anaerobic performance outcomes included: (i) jump height, (ii) critical power during a brief all-out cycling task, (iii) covering a short, given distance as quickly as possible (non-pacing task), and (iv) peak torque generation during a brief set of maximal contractions. Motor performance outcomes included: (i) accuracy/precision, (ii) reaction time/speed, and (iii) faults/false starts.

2.4 Risk of Bias

The Cochrane Risk of Bias Tool (RoB 2.0) was used to assess risk of bias in the included studies by two independent reviewers. For each included comparison, the RoB 2.0

tool designed for assessing the ‘effect of assignment to an intervention’ was used. Studies with between-subject design were assessed using the RoB 2.0 tool for randomized parallel group trials and studies using within-subject design were assessed using the RoB 2.0 tool for randomized cross-over trials. All outcomes of interest within the included studies were assessed for risk of bias arising from the randomization and allocation process, deviations from the intended interventions, missing outcome data, measurement of the outcome, and selection of the reported result. Domain-specific judgements of either low risk of bias, some risk of bias concerns, or high risk of bias were generated using the signalling questions within each domain (i.e., ‘yes/probably yes’, ‘no/probably no’, and ‘no information’), which were used to judge the overall risk of bias for each study. Disagreements between reviewers were resolved through discussion and consensus.

2.5 Data Syntheses

Due to the fact that physical performance measures varied across the included studies, Hedges’ g effect sizes and standard error (SE) were computed to summarize estimates of effects. Several studies did not report the standard deviations necessary to compute effect sizes; therefore, in these cases, other reported summary statistics (e.g., t values, p values) were used to approximate the missing values using the formulas described in Higgins and Green [36] and implemented in Comprehensive Meta-Analysis (CMA) software [37]. For between-subject studies employing pre–post intervention outcome measurements that did not report the standard deviation of the mean change or other summary statistics necessary to approximate an effect size, a comparison of the final outcome measure was used in the analysis if baseline measurements did not statistically differ as per recommendations in the Cochrane handbook for systematic reviews [36].

For studies that did not report pre–post correlation values necessary to approximate the effect size, available pre–post correlation values were imputed from previous studies that examined similar outcomes and used the same study design (when possible). Specifically, for between-group studies examining isometric resistance performance a computed average correlation value of 0.81 from three studies was used [26, 28, 38]. A computed average correlation value of 0.76 from three studies was used for within-subject isometric resistance performance [39–41]. A computed average value of 0.93 from three studies was used for studies examining aerobic performance using within-subject designs [31, 42, 43]. An average value of 0.51 from three studies was used for motor accuracy/precision performance [44–46] and an average value of 0.82 from two studies was used for motor reaction time/speed performance [45, 46].

If a study included a secondary experimental manipulation (e.g., persistence priming versus neutral priming) in a 2 (cognitive manipulation) × 2 (secondary manipulation) factorial arrangement, only the data for conditions that did not include a secondary manipulation were retrieved (e.g., high cognitive exertion + neutral condition compared to low cognitive exertion + neutral condition [39]). For studies comparing healthy populations against clinical populations, only data for the healthy conditions were included [29, 47]. If a study measured physical performance at multiple time points, only the pre-intervention and post-intervention outcomes were retrieved. For the one article that involved multiple conditions compared against one comparison control condition [26], the shared comparison condition was divided proportionally between each pairwise comparison to avoid a unit-of-analysis error (i.e., double counting) as per recommendations in the Cochrane handbook [36]. In six studies [48–52], discrete subsamples (e.g., athletes vs. untrained samples) were used which necessitated splitting each study into multiple comparisons. Similarly, in nine articles, more than one study was conducted and each substudy was included as an independent comparison [24, 39, 40, 50, 52–56]. Ten studies provided data for multiple effect sizes for one physical performance outcome [44, 57–64] and four studies provided effect sizes for different physical performance outcomes (i.e., aerobic and motor; maximal anaerobic, aerobic and motor) [22, 56, 65, 66]. In such cases, the multiple reported effect sizes were combined to create a single, composite effect size, as per recommendations by Borenstein et al. [67].

2.6 Meta-analysis

For the primary analysis, random-effects meta-analysis was computed in CMA software [37] to examine the effect of prior cognitive exertion on physical performance (all physical performance outcomes pooled). A forest plot of the main analysis was generated (see Electronic Supplementary Material 1: Figure S1). Heterogeneity was explored with the Cochrane Q (χ^2) test and summarized with the I^2 statistic. Publication bias was examined using Egger’s [68] test and Rosenthal’s [69] fail-safe N. Sensitivity analysis was computed in CMA software using one-study removed procedures. A figure containing the results of the sensitivity analyses was generated (Electronic Supplementary Material 2: Figure S2).

2.7 Subgroup Analyses

Subgroup analyses were computed in CMA software [37] to examine factors hypothesized to moderate the cognitive exertion–physical performance relationship based on theory and practical considerations. Effect sizes are presented as Hedges' g (standard error), with 95% confidence intervals (Z value, p value). Categorical variables included: publication status (published vs. unpublished), study design (within-subject vs. between-subjects), cognitive task manipulation duration (tasks lasting < 30 min vs. tasks lasting ≥ 30 min), and physical performance task type (aerobic, dynamic resistance, isometric resistance, maximal anaerobic, and motor performance). Differences between categorical variables within each subgroup analyses were computed using the Cochrane Q (χ^2) test.

3 Results

3.1 Included Studies

For the quantitative analysis, 73 articles provided a total of 91 comparisons with 2581 participants (not adjusted for within-subject designs) (see Electronic Supplementary Material 1: Figure S1). Publications included were conducted between 1998 and 2018. Study details and outcomes are presented in Table 1.

3.2 Risk of Bias

The overall risk of bias in each included study is presented in Electronic Supplementary Material 4: Table S2. No studies had low risk of bias, whereas 10 studies were judged as having some concerns and the remaining 81 studies were judged as high risk of bias. Risk of bias arising due to measurement of the outcome was most problematic as it was rated as high concern for bias in 81 of the 91 studies; this was partly due to inadequate blinding of personnel and outcome assessments.

3.3 Publication Bias

Egger's [68] test revealed significant publication bias ($t(89) = 5.91$, $p < 0.001$, two tailed). Rosenthal's [69] fail-safe N was significant ($Z = -19.00$, $p < 0.001$) and estimated that 8,461 null-effect studies would need to be included to result in a non-significant effect.

3.4 Heterogeneity

Results demonstrated significant heterogeneity for the overall effect, as well as each of the subgroup analyses, except for the four studies that involved multiple indices of physical performance, $Q(3) = 3.50$, $p = 0.32$, $T^2 = 0.01$, $I^2 = 14.17$, and the two studies that examined maximal anaerobic performance, $Q(1) = 0.60$, $p = 0.44$, $T^2 = 0.00$, $I^2 = 0.00$. Detailed results for the heterogeneity analyses are displayed in Table 2.

3.5 Sensitivity Analyses

Sensitivity analyses were performed to examine the between-comparison heterogeneity by removing one study at a time to evaluate the stability of the results. Summary results (see Electronic Supplementary Material 2: Figure S2) demonstrated stable significant effect sizes ranging from $g = -0.35$ (95% CI -0.42, -0.29) (when excluding the study by Brownsberger et al. [57]) to $g = -0.40$ (95% CI -0.48, -0.32) (when excluding the study by Zering et al. [70]).

3.6 Meta-analyses

3.6.1 Overall Effect

From the 73 studies, there were 91 independent comparisons for physical performance outcomes. Results showed that 81 of the 91 effect sizes were in the negative direction, of which 46 demonstrated a significant negative effect ($p < 0.05$) of prior cognitive exertion on physical task performance. Overall, findings demonstrated a significant small-to-medium negative effect, $g = -0.38$ (SE 0.04), 95% CI -0.46 to -0.31 ($Z = 10.44$, $p < 0.001$). Given the large I^2 value from the heterogeneity analysis, examination of the influence of moderating variables on the observed effects was further warranted. Detailed results for all moderators are displayed in Table 2 and findings are described below.

3.6.2 Study Design

Significant negative effects were observed for both within-subjects and between-group study designs. However, studies employing between-group designs had significantly larger effects than studies employing within-subject designs, $Q(1) = 13.21$, $p < 0.001$.

3.6.3 Publication Status

Significant negative effects were observed irrespective of publication status; however, results showed significantly larger effects in published studies compared to unpublished studies, $Q(1) = 7.70$, $p = 0.006$.

3.6.4 Duration of Cognitive Manipulation

Significant negative effects were observed for cognitive manipulations lasting < 30 min as well as those lasting ≥ 30 min. The magnitude of the effect sizes did not significantly differ by manipulation duration, $Q(1) = 3.85$, $p = 0.05$.

Table 1 Overview of study manipulations and outcomes

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Alberts et al., 2007 - Study 1 [100]	38 (19/19)	Undergraduate students	–	Between	Difficult labyrinths	Easy labyrinths	~ 10 min	–	Isometric endurance handgrip squeeze until failure (until coin fell)	–	↓ Time to failure
Alberts et al., 2007 - Study 2 [100]	40 (20/20)	Undergraduate students	–	Between	Attention control task	Addition	8 min	–	Submaximal isometric lateral raise until volitional exhaustion/failure	–	↓ Time to failure
Alberts et al., 2008 [101]	40 (20/20)	First year undergraduate psychology students	20.5 ± 1.8	Between	Star counting task	No instructions	3 min	No difference in subjective fatigue	Submaximal isometric lateral raise until volitional exhaustion	–	= Time to failure
Alberts et al., 2011 [39]	39 (20/19)	Undergraduate students	–	Between	Difficult arithmetic problems	Solve same calculations without auditory distraction	8 min	↑ Perception of difficulty	Isometric endurance handgrip squeeze until failure (until coin dropped)	–	↓ Time to failure
Azevedo et al., 2016 [102]	8	Males, $V0_2 = 45.2 \pm 3.0$ ml/kg per min	24 ± 2	Within	AX-CPT	Documentary	90 min	↑ POMS Fatigue subscale score	Cycling constant workload (80%max) until volitional exhaustion (aerobic)	↑	↓ Time to failure

Table 1 (continued)

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Badin et al., 2016 [44]	20	National soccer players	17.8 ± 1.0	Within	Stroop task	Documentary	30 min	↑ MF-VAS score	15-min 5v5 small-sided games (aerobic and motor performance measures)	↑	Motor: ↓ Control errors ↓ Passing accuracy ↓ Tackle success Aerobic:↓ High speed = Moderate speed = Low speed
Boat & Taylor, 2017 [103]	63	Young adults, recreationally active (4 ± 2days of exercise/wk)	22 ± 3	Within	Stroop task	Congruent Stroop task	4 min	↑ Rating of perceived mental exertion	Wall sit until volitional exhaustion/failure (isometric)	–	↓ Time to failure
Boat et al., 2017 [74]	14	Competitive endurance cyclists, 11 ± 6 hrs/week of training	20–52	Within	Stroop task	Congruent Stroop task	4 min	–	16km time trial on cycle ergometer (aerobic)	–	= Completion time
Bray et al., 2008 [22]	49 (23/26)	University students, sedentary	21.25 ± 1.70	Between	Stroop task	Congruent Stroop task	3 min 40 sec	No difference in fatigue or mental effort	Handgrip maximum voluntary contraction (anaerobic), isometric (50%MVC) endurance handgrip squeeze until volitional exhaustion/failure	–	= Peak force (anaerobic)↓ Time to failure (isometric)

Table 1 (continued)

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Bray et al., 2013 [94]	48 (24/24)	University students engaging in less than 2 weekly exercise sessions	22.26 ± 5.97	Between	Stroop task	Congruent Stroop task	5 min	↑ Perceived mental effort and tiredness	Isometric (50% MVC) endurance handgrip squeeze until volitional exhaustion/failure	–	↓ Time to failure
Bray et al., 2011 [25]	61 (28/33)	Older adults	71	Between	Stroop task	Congruent Stroop task	3 min 40 sec	↑ Perceived mental effort and tiredness	Isometric (50%MVC) endurance handgrip squeeze until volitional exhaustion/failure	–	↓ Time to failure
Brown & Bray, 2017 [26]	123 (21/20, 20,21,21,21)	Undergraduate students, untrained and recreationally active	19.87 ± 1.58	Between	Stroop task	Documentary	0,2,4,6,8,10 min	↑ MF-VAS score	Isometric (50% MVC) endurance handgrip squeeze until volitional exhaustion/failure	=	Time to failure: 0-min: =2-min: =4-min: = 6-min ↓ 8-min: ↓10-min: ↓
Brown & Bray, 2018 [31]	25	University students, <150min MVPA/week	20.16 ± 1.48	Within	AX-CPT	Documentary	50 min	↑ MF-VAS score	Total work in 30min of self-paced cycling (aerobic)	↓ Intended	↓ Total work
Brownsberger et al., 2013 [57]	12	Regular exercisers, VO_2 peak = 56 ± 6 ml/kg per min	24 ± 5	Within	AX-CPT	Documentary	90 min	↑ MF-VAS score	Mean power output during two 10-min bouts of self-paced exercise, one at RPE 11 and RPE 15 (aerobic)	Fixed	RPE 11: ↓ Power outputRPE 15: ↓ Power output

Table 1 (continued)

Study	N (control/ experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Ciarocco et al., 2001 - Study 2[a] [6]	24	Undergraduate students in introductory psychology	–	Between	Ostracism	Talk freely with confederate	3 min	↑ Negative affect	Isometric endurance handgrip squeeze until failure (until sponge fell)	–	↓ Time to failure
Coutinho et al., 2018 [104]	10	Amateur soccer players	13.7 ± 0.5	Within	Stroop (congruent & incongruent trials)	No task	30 min	No comparison for control condition	Total distance covered in a 5-a-side small-sided soccer game (aerobic)	–	↓ Total distance
Dorris et al., 2012 – Experiment 1 [54]	24	Competitive male rowers	> 18	Within	Arithmetic while balancing spirit level	Counting backwards from 1000 by 5s while standing	Not standardized	No difference in perceived mental effort	Complete as many press-ups (push-ups) as possible until failure (dynamic resistance)	–	↓ Push-ups completed
Dorris et al., 2012 – Experiment 2 [54]	24	University students, hockey and rugby players	–	Within	Arithmetic while balancing spirit level	Counting backwards from 1000 by 5s while standing	Not standardized	↑ Perceived mental effort	Complete as many sit-ups as possible until failure (dynamic resistance)	–	↓ Sit-ups completed
Duncan et al., 2015[a] [105]	8	University students, physically trained, from team sports including: rugby, football, & basketball	24.8 ± 4.1	Within	Concentration grids	Documentary	40 min	–	Mean power output throughout four 30 sec Wingate tests (anaerobic)	–	= Mean cycling power
Englert & Bertrams, 2012 - Study 1 [55]	64 (32/32)	Amateur male basketball players	22.92 ± 6.11	Between	Text transcription – with omission	Text transcription	6 min	↑ Perceived task difficulty, effort, and feelings of depletion	Basketball free throw accuracy (motor)	–	= Number of baskets /10 attempts

Table 1 (continued)

Study	N (control/ experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Englert & Bertrams, 2012 - Study 2 [55]	40 (21/19)	University students	22.27 ± 3.39	Between	Text transcription – with omission	Text transcription	6 min	↑ Perceived task difficulty, effort, and feelings of depletion	Dart throwing accuracy (motor)	–	= Dart throwing accuracy
Englert & Bertrams, 2014 [106]	37 (19/18)	University sport students, sprint experience	22.05 ± 1.89	Between	Crossing out letters task	Transcribing neutral text	6 min	↑ Perceived effort	Sprint start reaction time (motor)	–	↑ Reaction time
Englert & Wolff, 2015 [107]	20	University sport students	25.00 ± 1.84	Within	Stroop task	Congruent Stroop task	Time to complete 80 trials of Stroop (time not reported)	No difference in positive or negative mood	Cycle as fast as possible for 18 min at fixed workload (aerobic)	–	↓ bpm and rpm
Englert et al., 2015 [108]	31 (15/16)	Experienced male basketball players	29.26 ± 4.90	Between	Text transcription – with omission	Transcription task without omissions	6 min	↑ Perceived depletion	Basketball free throw percentage (/30) in distracting environment (motor)	–	↓ Free throw percentage
Englert et al., 2015 [109]	38 (19/19)	University level female soccer players, 14.13 ± 3.88 years of experience	20.58 ± 2.10	Between	Text transcription – with omission	Transcribing neutral text	6 min	↑ Perceived depletion	Sprint starts (motor)	–	↑ False starts
Filipas et al., 2018 [110]	17	Young rowers	11 ± 1.06	Within	Stroop task	Coloring	60 min	↑ Mental demand and effort	1500m time trial on rower-ergometer (aerobic)	=	= Completion time
Finkel et al., 2006 - Study 4 [111]	32	Undergraduate students	19.52 ± 1.12	Within	Inefficient social coordination	Efficient social coordination (non-depressed low-maintenance)	6 min	No difference in subjectively experienced depletion	Isometric endurance handgrip squeeze until failure (until eraser dropped)	–	↓ Time to failure

Table 1 (continued)

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Graham & Bray, 2012 [28]	24 (9/15)	University students engaging in less than 2 weekly exercise sessions	21.60 ± 4.00	Between	Guided imagery	Quiet rest	6 min	↑ Perceived mental effort and tiredness	Isometric (30% MVC) endurance handgrip squeeze until volitional exhaustion/failure	–	= Time to failure
Graham & Bray, 2015 [78]	37 (18/19)	University students, < 90 min/week MVPA, no resistance training during last 6 months	21.48 ± 2.93	Between	Stroop task	Congruent Stroop task	5 min	↑ Rating of perceived mental exertion	Isometric (50%MVC) endurance handgrip squeeze until volitional exhaustion/failure	=	↓ Time to failure
Graham et al., 2017 [58]	50 (25/25)	University students, < 150 min/week MVPA	20.98 ± 2.83	Between	Stroop task	Congruent Stroop task	5 min	↑ Rating of perceived mental exertion	Seated bench press at 60% 1RM and leg extension at 40% 1RM until failure (dynamic resistance)	–	↓ Repetitions completed for bench press and leg extensions
Graham et al., 2018 [112]	70 (33/37)	Children at summer sports camp	10.14 ± 1.90	Between	Stroop task	Congruent Stroop task	5 min	↑ Rating of perceived mental exertion	Isometric (30% MVC) endurance handgrip squeeze until volitional exhaustion/failure	=	↓ Time to fatigue
Graham et al., 2014 [113]	50 (25/25)	University students	20.90 ± 3.05	Between	Imagery	Quiet rest	3 min	↑ Rating of perceived mental exertion	Isometric (50%MVC) endurance handgrip squeeze until volitional exhaustion/failure	–	↓ Time to failure

Table 1 (continued)

Study	N (control/ experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Hagger et al., 2013 - Study 1 [40]	19	Undergraduate students, regular cigarette smokers	23.47 ± 3.01	Within	Cue exposure task -cigarettes	Neutral image exposure task	~ 5.5 min	–	Isometric endurance handgrip squeeze until failure (until coin dropped)	–	↓ Time to failure
Hagger et al., 2013 - Study 2 [40]	32	Undergraduate students, regular cigarette smokers	20.13 ± 1.41	Within	Cue exposure task -cigarettes	Cue exposure task with straws	~ 15 min	–	Isometric endurance handgrip squeeze until failure (until coin dropped)	–	↓ Time to failure
Head et al., 2016 [59]	18	Young adults, at least 6 months experience participating in high intensity exercise routines	28 ± 3.8	Within	Computerized Vigilance task (low go/ high no-go)	Documentary	52 min	–	High intensity body resistance exercise routine repeated as many times as possible in 20 minutes (dynamic resistance)	=	= Repetitions completed↑ Time on task
Head et al., 2017 [60]	20	Male infantry soldiers from US, extensively trained in rifle marksmanship	–	Within	Response inhibition (SART)	Documentary	49 min	↑ Subjective mental workload	Marksmanship (motor)	–	= Accuracy = DCSG ↑ Errors of commission = Errors of omission = Response time = SGP
Le Mansec et al., 2017 [45]	5	Regional-national level male table tennis players	26.9 ± 8.9	Partial crossover	AX-CPT	Documentary	90 min	↑ MF-VAS score	Table tennis performance (motor)	=	↓ Total score (↓ ball speed, ↓ accuracy, ↑ faults)

Table 1 (continued)

Study	N (control/ experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Leung et al., 2014 [47]	20 (10/10)	Healthy controls matched to patients with schizophrenia for age, gender, and education	Exp: 30.9 ± 12.3 Control: 34.7 ± 12.6	Between	Crossing out letters task	Letter deletion task (only cross out C & F)	One passage of text	–	Isometric endurance handgrip squeeze until failure (until coin dropped)	–	↓ Time to failure
MacMahon et al., 2014 [114]	20	Young adults, currently running 2.84 ± 1.79 hrs/week, familiar with 3km run distance	25.4 ± 3.24	Within	AX-CPT	Documentary; 3min AX-CPT before and after documentary	90 min	↑ POMS fatigue subscale score	3km time trial running on indoor track (aerobic)	=	↑ Completion time
Marcora et al., 2009 [95]	16	Young adults, engaging in regular aerobic exercise, VO_{2peak} = 52 ± 8 ml/kg per min	26 ± 3	Within	AX-CPT	Documentary	90 min	↑ BRUMS fatigue subscale score	Cycling at 80% peak workload until volitional exhaustion (aerobic)	=	↓ Time to exhaustion
Martijn et al., 2007[a] [115]	77	Undergraduate students	–	Between	Difficult labyrinths	Solve easy labyrinths	10 min	–	Isometric endurance handgrip squeeze until failure (until match fell)	–	↓ Time to failure
Martijn et al., 2002 - Study 1 [7]	33 (16/17)	Undergraduate students		Between	Emotion suppression	Watch same video without instructions to suppress emotions	3 min	No difference in POMS fatigue subscale score	Isometric endurance handgrip squeeze until failure (until match dropped)	–	↓ Time to failure

Table 1 (continued)

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Martin et al., 2015 [61]	12	Young adults, high intensity training 3x/week, peak oxygen uptake = 53 ± 13 L/min)	23 ± 3	Within	AX-CPT	Documentary	90 min	↑ Perceived mental effort, no difference in perceived tiredness	Countermovement jump (anaerobic) isometric maximal knee extension (anaerobic)3 min all-out cycling test (anaerobic)	=	= Jump height= Peak torque= Critical power
Martin et al., 2016 [49]	20	Professional male road cyclists (n = 11); peak power output= 414 ± 48Wrecreational male road cyclists (n = 9); peak power output= 261 ± 28W	Pro: 23.4 ± 6.4 Rec: 25.6 ± 5.3	Within	Stroop task	Focus on black cross in center of screen	30 min	↑ Perceived mental effort	Maximal distance test in 20 minutes on cycle ergometer (aerobic)	=	Professional cyclists: = Distance covered= Speed Recreational cyclists: ↓ Distance covered ↓ Speed
Martin Ginis & Bray, 2010 [96]	61 (30/31)	University students	20 ± 2.4	Between	Stroop task	Congruent Stroop task	3 min 40 sec	No difference in subjective fatigue	Work generated in 10min bout on cycle ergometer (aerobic)	Fixed	↓ Work output
McEwan et al., 2013 [62]	62 (31/31)	Young adults, inexperienced dart players	22.8 ± 3.95	Between	Stroop task	Congruent Stroop task	5 min	No difference in MF-VAS score	Dart throwing (motor)	–	↓ Accuracy= Reaction time
Molden et al., 2012 - Experiment 2 [77]	44 (22/22)	University students	18.84 ± 0.57	Between	Perceptual vigilance task	Crossing out all e's	Time to read one page of text	–	Isometric endurance handgrip squeeze until failure (until wad of paper fell)	–	↓ Time to failure

Table 1 (continued)

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Muraven et al., 1998 - Study 1 [8]	40 (20/20)	Undergraduate students in introductory psychology	–	Between	Regulating emotions watching video clip	Watch same video without instructions to suppress emotions	3 min	↑ Subjective fatigue	Isometric endurance handgrip squeeze until failure (until wad of paper fell)	–	↓ Time to failure
Murtagh & Todd, 2004 - Study 1 [116]	69 (27/42)	Undergraduate students, predominantly Caucasian	21.4	Between	Stroop task	Congruent Stroop task	15 min	–	Isometric endurance handgrip squeeze until failure (until cloth ball fell)	–	= Time to failure
Otani et al., 2017 [42]	8	Young adult males, VO_{2max}= 45.2 ± 6 mL/min/Kg	22 ± 0.6	Within	Stroop task; Sternberg paradigm; Rapid visual info processing	Documentary	90 min	↑ Self-reported MF	Cycling at 80% VO_{2max} until volitional exhaustion/failure (aerobic)	=	↓ Time to failure
Pageaux et al., 2013 [66]	10	Physically active male adults	22 ± 2	Within	AX-CPT	Documentary	90 min	↑ BRUMS fatigue subscale score	Leg extension maximum voluntary contraction (anaerobic), isometric (20% MVC) knee contraction until volitional exhaustion/failure	↑	= Peak torque (anaerobic)↓ Time to failure (isometric)

Table 1 (continued)

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Pageaux et al., 2014 [19]	12	Young adults, at least 6 months experience participating in aerobic exercise	21 ± 1	Within	Stroop task	Congruent Stroop task	30 min	No difference in BRUMS fatigue subscale, ↑ perceived mental demand and mental effort	5km time trial on treadmill (aerobic)	↑	↑ Completion time
Pageaux et al., 2015 [117]	12	Physically active adult males	25 ± 4	Within	Stroop task	Congruent Stroop task	30 min	No difference in BRUMS fatigue subscale, ↑ perceived mental demand and mental effort	Leg extension maximum voluntary contraction	–	= Peak torque
Penna et al., 2018 [43]	16	Youth swimmers competing at state or national level with 7.35 ± 2.2 years of swimming experience and training an average of 30,000m/week	15.45 ± 0.51	Within	Stroop task	Documentary	30 min	↑ MF-VAS score	1500m swimming time trial (aerobic)	=	↑ Completion time
Pires et al., 2018 [93]	8	Male recreational cyclists	29.3 ± 7.9	Within	Rapid visual information processing test	Rest	30 min	No difference in POMS fatigue subscale	20km time trial on road bike cycle simulator (aerobic)	Faster increase	↑ Completion time ↓ Mean wattage

Table 1 (continued)

Study	N (control/ experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Roussey et al., 2018 [118]	11	Trained male cyclists, $VO_{2peak} = 63 \pm 5$ ml/kg per min	27.0 ± 8.6	Within	Stroop task	Documentary	60 min	No difference in BRUMS fatigue subscale, ↑ perceived mental demand and mental effort	Cycling at RPE = 15 for 30 min (aerobic)	Fixed	= Mean power output
Salam et al., 2018 [63]	11	Trained male cyclists, $VO_{2peak} = 60.4 \pm 4.1$ ml/kg per min	38 ± 6	Within	Stroop task	Reading “emotionally neutral” magazines	30 min	↑ MF on 10-point scale	Time to exhaustion on cycle ergometer at 40%, 60%, 80% and 100% of VO_{2peak} (aerobic)	↑	↓ Time to exhaustion at 40%, 60%, 80% and 100% of VO_{2peak}
Schucker & MacMahon, 2016 - Study 1 [53]	12	Trained athletes (n = 6 team sport athletes and n = 6 endurance athletes)	29.41 ± 14.47	Within	Stroop task	Congruent Stroop task	10 min	↑ Subjective MF	Beep test (aerobic)	↑	= Completion time
Schucker & MacMahon, 2016 - Study 2 [53]	11	Trained athletes	30.64 ± 13.11	Within	Stroop task	Documentary	10 min	No difference in subjective MF, ↑ perceived effort	Beep test (aerobic)	=	= Completion time
Seeley & Gardner, 2003 - Study 1[a] [56]	112	University students	–	Between	White bear thought suppression	Free thinking	5 min	–	Isometric endurance handgrip squeeze until failure (until paper fell)	–	↓ Time to failure

Table 1 (continued)

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Seeley & Gardner, 2003 - Study 2 [56]	151	University students	–	Between	White bear thought suppression	Free thinking	5 min	–	Isometric endurance handgrip squeeze until failure (until paper fell)	–	↓ Time to failure
Shortz & Mehta, 2017 [51]	20	Younger (n = 10) and older (n = 10) women	Younger: 24.10 ± 1.79 older: 75.90 ± 7.80	Within	Stroop task; 1-back test	Documentary and/or read magazines	60 min	↑ POMS fatigue subscale score for older and younger	Intermittent submaximal (30%MVC) handgrip squeezes until volitional exhaustion/failure (isometric)	–	Older women: ↓ Time to failure Young women: = Time to failure
Shortz et al., 2015[a] [119]	11	Older female adults, < 90 min/week MVPA	75.82 ± 7.4	Within	Stroop task; 1-back test	Documentary	60 min	↑ POMS fatigue subscale score	Intermittent submaximal (30%MVC) handgrip squeezes until volitional exhaustion/failure	–	↓ Time to failure
Silva-Cavalcante et al., 2018 [120]	8	Recreationally trained male cyclists	33.8 ± 7.2	Within	AX-CPT	Documentary	90 min	↑ MF-VAS score	4km cycling time trial (aerobic)	=	= Completion time
Smith et al, 2016 [46]	12	Male soccer players, 13 ± 2.6 years of experience	19.3 ± 1.5	Within	Stroop task	Reading "emotionally neutral" magazines	30 min	↑ MF-VAS score	Soccer-specific decision-making task (response accuracy, response time)	–	↓ Response accuracy ↓ Response times
Smith et al, 2016 - Study 1 [24]	12	Male recreational soccer players	24 ± 0.4	Within	Stroop task	Reading "emotionally neutral" magazines	30 min	↑ MF-VAS score	Yo-Yo IR1 test (aerobic)	↑	↓ Distance covered

Table 1 (continued)

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Smith et al, 2016 - Study 2 [24]	14	Trained male competitive players with 13.6 ± 3.2 years of experience	19.6 ± 3.5	Within	Stroop task	Reading "emotionally neutral" magazines	30 min	↑ MF-VAS score	Loughborough soccer passing and shooting tests (motor)	–	Passing: = Original time ↑ Penalty timeShooting: ↓ Points per shot ↓ Shot speed
Smith et al., 2015 [64]	10	Male members of competitive intermittent sports teams, VO2max: 48 ± 6 mL/kg per min	22 ± 2	Within	AX-CPT	Documentary	90 min	↑ BRUMS fatigue subscale score	Self-paced intermittent running (distance, velocity, and work)	↑	↓ Overall velocity ↓ Total distance= Total work
Stocker et al., 2018 [121]	34 (18/16)	First year university students	20.85 ± 1.31	Between	Transcription task – with omission	Transcribe verbatim	6 min	↑ Perceived task difficulty/effort	Isometric plank until failure	–	= Time to failure
Tyler & Burns, 2008 - Experiment 1 [75]	20 (10/10)	Undergraduate students in introductory psychology	–	Between	Arithmetic while standing on one leg	Counting backwards from 2000 by 5s while standing	6 min	↑ Perceived task difficulty	Isometric endurance handgrip squeeze until failure (until sponge fell)	–	↓ Time to failure
Tyler & Burns, 2009 - Experiment 2 [52]	60 (10 per group, 6 groups)	Undergraduate students	–	Between	Crossing out letters task	Crossing out all e's	3 min, 10 min, 20 min	↑ Perceived task difficulty	Isometric endurance handgrip squeeze until failure (until sponge fell)	–	↓ Time to failure
Veness et al., 2017 [65]	10	Elite male cricket players, minimum 2 years training	21 ± 8	Within	Stroop task	Reading "emotionally neutral" magazines	30 min	↑ MF-VAS score	Cricket run-two test (anaerobic) Batak Lite (motor) Yo-Yo test (aerobic)	↑	↑ Run-two test time = Batak lite ↑ Yo-Yo test time

Table 1 (continued)

Study	N (control/experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Vohs et al., 2005 - Study 2[a] [122]	–	Undergraduate students	–	Between	Impression formation	Impression task without self-regulation	~10 min	No difference in positive or negative affect on PANAS	Isometric endurance handgrip squeeze until failure (until sponge fell)	–	= Time to failure
Vrijkotte et al., 2018 [123]	9	Trained male cyclists, $VO_{2max} = 61.67 \pm 5.05$ ml/kg per min	26 ± 6	Within	Stroop task	Rest	90 min	↑ MF-VAS score	Wattage achieved on graded exercise test (40 watt increase every 3min until failure) on cycle ergometer (aerobic)	=	= Maximum wattage
Wagstaff, 2014 [124]	20	Male undergraduate students, competitive endurance athletes	21.13 ± 1.61	Within	Regulate emotions while watching video clip	Watch same video without instructions to suppress emotions	3 min	No difference in BMIS scores	Complete 10km as fast as possible on cycle ergometer at fixed workload (aerobic)	↑	↑ Completion time
Xu et al., 2014 [41]	102	Community adults and young adults	Community: 41.6 ± 15.3 Young: 19.7 ± 1.3	Within	Crossing out letters task	Cross out every instance of the letter “e”	8 min	–	Isometric (70%MVC) endurance handgrip squeeze until volitional exhaustion/failure	–	= Time to failure
Yusainy & Lawrence, 2015 [38]	55 (28/27)	Native British young adults	19.52 ± 2.03	Between	Attention control task	Attention control task (watching video) with no instructions (could read subtitles)	6 min	No difference in perceived task difficulty	Isometric endurance handgrip squeeze until failure (until wad of paper fell)	–	↓ Time to failure

Table 1 (continued)

Study	N (control/ experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Zering et al., 2016 [70]	15	University students, recreationally active (6±2 sessions of >10min/ week)	19.56 ± 1.69	Within	Stop-signal task	Documentary	10.5 min	↑ Rating of perceived mental exertion	Peak power achieved on graded exercise test at volitional exhaustion/failure (aerobic)	↑	↓ Peak power
Unpublished Studies											
Boat & Taylor [48]	9	Trained endurance cyclists	23–28	Within	Stroop task	Congruent Stroop task	16 min	↑ Rating of perceived mental exertion	16km time trial on cycle ergometer (aerobic)	–	= Completion time
Boat & Taylor [48]	9	Trained endurance cyclists	23–28	Within	Stroop task	Congruent Stroop task	4 min	↑ Rating of perceived mental exertion	16km time trial on cycle ergometer (aerobic)	–	↑ Completion time
Brown & Bray [27]	36	University students	19.44 ± 1.42	Within	Stroop task	Documentary	10 min	↑ MF-VAS area under the curve	Work accumulated in 20min of self-paced cycling (aerobic)	=	↓ Total work
Graham - Study 3 [125]	24 (11/13)	University students, <90min moderate-vigorous intensity physical activity/week	19.88 ± 4.22	Between	Stroop task	Congruent Stroop task	5 min	↑ Rating of perceived mental exertion	Isometric (50%MVC) endurance handgrip squeeze until volitional exhaustion/ failure	=	↓ Time to failure
Langvee & Bray [126]	18	University students, < 210min vigorous cardio/week	19.78 ± 1.52	Within	Stroop task	Documentary	10 min	–	Time to failure at 65% peak workload on cycle ergometer (aerobic)	–	= Time to failure

Table 1 (continued)

Study	N (control/ experimental)	Sample characteristics	Age (mean ± SD)	Design	Cognitive task	Control task	Cognitive task duration	Intermediary measure	Physical task	RPE	Results
Langvee [127]	16	Undergraduate students, ≥ 150min MVPA/ week	20.94 ± 2.21	Within	Thought suppression task	Thought listening (without constraints)	6 min	↑ MF-VAS score	Maximal distance trial in 20min on cycle ergometer (aerobic)	–	= Distance
Lubusko, 2005 [29]	54 (27/27)	University students	24.72 ± 6.07	Between	CPT	Arithmetic task	~14 min	↑ BMIS fatigue subscale score	Isometric endurance handgrip squeeze until failure (until paper fell)	–	↓ Time to failure
MacMahon et al. [128]	14	Athletically active	–	Within	Stroop task	Congruent Stroop task	30 min	↑ Perceived fatigue on 1–7 point scale	Time to failure on Beep test (aerobic)	=	↑ Completion time
Schucker et al. - Study 1 [50]	40	20 athletes, 20 non-trained	–	Within	Counting backward from 1000 by 7s	Counting forward by 5s	–	–	Reps to failure on sit ups (dynamic resistance)	=	↓ Reps to failure
Schucker et al. -Study 2 [50]	26 (13/13) 33 (16/17)	26 trained, 33 untrained	–	Between	Stroop task	Congruent Stroop task	–	–	Time to failure on wall sit (isometric)	=	= Time to failure

1RM one repetition maximum, *AX-CPT* AX continuous performance task, *BMIS* Brief Mood Introspection Scale, *bpm* beats per minute, *BRUMS* Brunel Mood Scale, *CPT* continuous performance task, *DCSG* Distance of the Center of the Shot Group, *km* kilometers, *MF* Mental Fatigue, *MF-VAS* Mental Fatigue Visual Analogue Scale, *MVC* maximal voluntary contraction, *MVPA* moderate to vigorous physical activity, *PANAS* positive and negative affect schedule, *POMS* profile of mood states, *RPE* rating of perceived exertion, *rpm* revolutions per minute, *SART* sustained attention to response task, *SD* standard deviation, *SGP* shot group precision, VO_2 maximal oxygen uptake, *W* watts

[a] Insufficient data to include in meta-analysis. Arrows indicate direction of effect following cognitive exertion condition in comparison to control condition; = indicates no significant difference between conditions

Table 2 Effect sizes

	Q (*df*)	I^2	T^2	*n* ES	Hedges' *g* [95% CI]	SE	*Z*	*p*
Overall	469.48 (90)	80.83	0.78	91	−0.38 [−0.46, −0.31]	0.04	−10.44	< 0.001
Moderators								
Study design								
Within-subject	303.57 (51)	83.20	0.05	52	−0.28 [−0.36, −0.21]	0.04	−7.41	< 0.001
Between-subjects	110.53 (38)	65.62	0.22	39	−0.65 [−0.84, −0.47]	0.09	−6.92	< 0.001
Publication status								
Published	422.99 (78)	81.56	0.08	79	−0.42 [−0.50, −0.34]	0.04	−9.97	< 0.001
Unpublished	37.32 (11)	70.53	0.03	12	−0.20 [−0.33, −0.07]	0.07	−2.92	0.003
Duration of cognitive manipulation								
< 30 min	301.46 (58)	80.76	0.08	59	−0.45 [−0.55, −0.35]	0.05	−8.82	< 0.001
≥ 30 min	167.71 (31)	81.52	0.06	32	−0.30 [−0.41, −0.20]	0.06	−5.52	< 0.001
Physical performance indices								
Aerobic	188.39 (31)	83.55	0.04	32	−0.26 [−0.34, −0.18]	0.04	−5.99	< 0.001
Isometric resistance	188.93 (36)	80.95	0.21	37	−0.57 [−0.75, −0.39]	0.09	−6.10	< 0.001
Dynamic resistance	13.77 (5)	63.68	0.07	6	−0.51 [−0.77, −0.24]	0.13	−3.78	< 0.001
Motor	18.55 (9)	51.49	0.10	10	−0.57 [−0.85, −0.30]	0.14	−4.06	< 0.001
Maximal anaerobic	0.60 (1)	0.00	0.00	2	0.10 [−0.07, 0.26]	0.09	1.11	0.27
Multiple indices of physical performance	3.50 (3)	14.35	0.01	4	−0.27 [−0.48, −0.06]	0.11	−2.50	0.01
Physical performance indices for cognitive manipulations < 30 min								
Aerobic	47.62 (12)	74.80	0.02	13	−0.17 [−0.27, −0.07]	0.05	−3.36	0.001
Isometric resistance	177.80 (34)	80.88	0.21	35	−0.60 [−0.79, −0.41]	0.10	−6.22	< 0.001
Dynamic resistance	13.61 (4)	70.61	0.09	5	−0.56 [−0.87, −0.24]	0.16	−3.48	< 0.001
Motor	14.79 (5)	66.20	0.18	6	−0.61 [−1.03, −0.18]	0.22	−2.81	0.005
Maximal anaerobic	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Multiple indices of physical performance	0.04 (1)	0.00	0.00	2	−0.31 [−0.68, 0.06]	0.19	−1.66	0.10
Physical performance indices for cognitive manipulations > 30 min								
Aerobic	132.92 (18)	86.46	0.07	19	−0.35 [−0.49, −0.21]	0.07	−4.92	< 0.001
Isometric resistance	7.94 (1)	87.41	0.31	2	−0.11 [−0.94, 0.71]	0.42	−0.27	0.79
Dynamic resistance	N/A	N/A	N/A	1	−0.29 [−0.75, 0.17]	0.23	−1.24	0.22
Motor	3.71 (3)	19.21	0.02	4	−0.50 [−0.84, −0.17]	0.17	−2.96	0.003
Maximal anaerobic	0.60 (1)	0.00	0.00	2	0.10 [−0.07, 0.26]	0.09	1.11	0.27
Multiple indices of physical performance	3.29 (1)	69.62	0.15	2	−0.42 [−1.05, 0.21]	0.32	−1.30	0.19

3.6.5 Physical Performance Indices

Negative carryover effects associated with prior cognitive exertion were significantly different depending on the physical task requirements, $Q(5) = 36.29$, $p < 0.001$. The largest significant negative effects were those of prior cognitive exertion on isometric resistance, motor and dynamic resistance performance. A smaller significant negative effect was found for aerobic exercise performance and tasks involving multiple indices of physical performance, whereas a null effect was observed for the two comparisons that examined maximal anaerobic performance.

3.6.6 Physical Performance Indices by Duration of Cognitive Manipulation

The results showed significant variation between the effect sizes for the different physical performance indices when considering the duration of the cognitive manipulation, $Q(10) = 43.06$, $p < 0.001$. Specifically, following exposure to cognitive manipulations < 30 min, the largest significant negative effects were observed for isometric resistance, dynamic resistance, and motor performance tasks, whereas a smaller significant negative effect was found for aerobic performance. A null effect was observed for the two studies with cognitive manipulations lasting < 30 min that involved multiple indices of physical performance. There were no studies with cognitive manipulations lasting < 30 min that examined maximal anaerobic performance.[3] For cognitive manipulations lasting ≥ 30 min, significant negative effects were observed for aerobic and motor performance, whereas null effects were observed for isometric resistance, dynamic resistance, maximal anaerobic performance and studies that involved multiple indices of physical performance.

4 Discussion

The purpose of the present work was to conduct a systematic review and meta-analysis of studies investigating the effect of prior cognitive exertion on physical performance and to examine moderators of this relationship. Results of the main analysis showed that exposure to a task requiring cognitive exertion has a significant, small-to-medium sized negative effect on subsequent physical performance ($g = -0.38$) and significant heterogeneity in the data. Several subgroup/moderator analyses also showed significant effects. Study design type revealed a medium-sized negative effect for between-group designs ($g = -0.65$), whereas a small negative effect size was found for within-subject designs ($g = -0.28$). For publication status, larger negative effects were observed for published studies ($g = -0.42$) compared to unpublished research ($g = -0.20$). Type of physical performance task was also a moderator, with prior cognitive exertion having significant negative effects on motor performance ($g = -0.57$) and tasks requiring prolonged effort regulation (i.e., aerobic [$g = -0.26$], isometric resistance [$g = -0.57$], dynamic resistance performance [$g = -0.51$]), whereas tasks requiring maximal anaerobic performance showed trivial effects that were not significant. Findings revealed similar small-to-medium negative carryover effects for cognitive tasks < 30 min ($g = -0.45$) as well as those lasting ≥ 30 min ($g = -0.30$). Together, the results provide a comprehensive description of the state of the literature investigating the relationship between prior cognitive exertion and physical performance as of September, 2018. Importantly, the results indicate conclusions proposed by McMorris and colleagues [5] based on the results of their meta-analysis underestimated the overall effect.

Conducting a comprehensive meta-analysis of the literature examining the relationship between prior cognitive exertion and physical performance revealed a significant small-to-medium sized negative effect when all types of physical performance tasks, study designs, and experimental manipulation durations were considered. In contrast to the conclusions offered by McMorris et al. [5], heterogeneity tests in the current meta-analysis suggest that the overall effect is not due to random error and is relatively stable as per results of a sensitivity analysis. The results of Rosenthal's [69] fail-safe *N* test further suggest that the current findings are not due to chance, as nearly 8500 null findings would be needed to observe a non-significant effect.

Our inclusion of a large sample of comparisons provided greater power to interpret heterogeneity tests (i.e., Cochrane's *Q*, tau-squared), which may otherwise be skewed by smaller samples [67, 71] as in the meta-analysis by McMorris et al. [5]. In a published critique of McMorris et al.'s meta-analysis [5], Magariño and Madhivanan [72] expressed concerns regarding the comprehensiveness, replicability, and rationale for the exclusion criteria. For instance, those authors attempted to replicate McMorris et al.'s [5] search protocol within PubMed (one of the two databases explored for the meta-analysis) using the keywords reported in the paper. Results of that search identified over 14,000 citations compared to the 93 reported by McMorris et al. [5]. In response to the criticisms raised by Magariño and Madhivanan [72], McMorris et al. [73] revealed that, contrary to what was reported in the published paper, their actual search had left out the term "physical" and included only the following search term combinations: "cognitive AND fatigue AND subsequent AND performance" and "cognitive AND fatigue AND subsequent AND exercise." Therefore, not including the keyword "physical" as outlined in their methodology appears to have limited the thoroughness of their literature search. In the present review, we have shown that using a greater sample of studies reduced potential selection bias, which may have affected the results of previous reviews and meta-analyses in the area.

Recent reviews have suggested that cognitive manipulations need to be ≥ 30 min in duration to induce mental fatigue and, in turn, impair physical performance. However, as we argued above, there does not appear to be any sound theorizing or empirical evidence upon which to base this assertion. In fact, the present findings revealed similar small-to-medium sized negative carryover effects on physical performance for cognitive task manipulations lasting < 30 min as well as those ≥ 30 min. To more fully explore this issue, we conducted a post-hoc meta-regression of the relationship between cognitive task duration and physical performance. The results showed no evidence of a linear dose–response relationship ($\beta = 0.00 \pm 0.00$, $p = 0.18$). Closer examination of the literature reveals that negative carryover effects occur following manipulations lasting as little as 3–5 min [22, 74, 75]. Other evidence suggests that a threshold effect may exist, whereby negative carryover effects may not reliably

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[3] Bray et al. [22] examined maximal anaerobic performance ($d = 0.05$) and isometric performance ($d = 0.50$) and was, therefore classified as multiple indices of physical performance.

occur following cognitive manipulations lasting 4 min or less, but are evident following manipulations that are 6 min in duration or longer [26]. Studies have also shown that negative carryover effects observed following brief cognitive manipulations tend to dissipate after extended periods of cognitive exertion (Boat and Taylor [48]; Wolff et al. [76]), which suggests that a potential curvilinear relationship may exist. In sum, there appears to be no simple time-based gradient that alters the magnitude of the negative effect of prior cognitive exertion on physical performance. However, future work should investigate whether an effort- or fatigue-based gradient or curvilinear relationship exists.

Another important discovery revealed by our subgroup analyses of moderating factors was that studies employing between-group designs show a twofold larger effect ($g = -0.65$) compared to within-subject designs ($g = -0.28$) and, notably, the average effect size observed in our analysis of within-subject designs was nearly identical to the $g = -0.26$ effect size reported by McMorris et al. [5]. It is important to recognize that seven of the ten largest effect sizes were found in studies using between-group designs. Of these seven studies, four quantified ego-depletion effects by measuring the amount of time a participant could squeeze an object (e.g., sponge, coin, wad of paper) between the two handles of a spring-loaded handgrip exercise device following an initial task requiring cognitive exertion [47, 52, 75, 77]. This method of measurement lacks precision as grip force requirements are not calibrated to individual grip strength and small adjustments of the hand may have caused objects to prematurely fall out from between the handgrip handles, signalling completion of the trial and potentially biasing the effect sizes observed. Researchers have since adopted more sophisticated procedures such as using a computer monitor to display a static line with an individualized target force level (e.g., 50% of participant's maximum voluntary contraction) alongside real-time feedback showing a tracing of the participant's force generation [26, 78]. Doing so allows for minor corrective adjustments when the force falls below the target level for brief intervals (e.g., < 2 s), only to be stopped when the force falls below the target level for a specified duration. Thus, ego-depletion studies using somewhat primitive methodology to determine the dependent measures may have inflated the average between-group study effect size.

Subgroup analysis of publication status also revealed a significant difference between published and unpublished research. This finding is indicative of publication bias in the sample of studies included in the analyses, with the majority of the unpublished studies showing small, non-significant effects. However, the greater power of meta-analysis also provides evidence that the negative effect observed in unpublished studies is not due to chance. It is interesting to note that very few unpublished studies were discovered through our efforts to contact authors of published literature and, of these studies, many were in various stages of preparation for publication. The small number of the unpublished experiments included in the present analysis is interesting in light of recent findings by Wolff et al. [79], which showed that researchers working in the broader ego-depletion research field have reported completing nearly as many studies which had not been published ($M = 2.68 \pm 4.13$) as those that had been published ($M = 3.40 \pm 7.48$). While ego-depletion researchers in sport science represented only a small percentage (5.1%) of Wolff et al.'s [79] sample, it is possible that journals in this area are more receptive to publishing studies with null findings. Moving forward, researchers of the mental fatigue/ego depletion—physical performance relationship are encouraged to invest effort in publishing studies with non-significant effects, as sharing the results of such studies will help direct research efforts to detect and better understand moderators or boundary conditions of the effect.

Building on previous work of Pageaux and Lepers [3], subgroup analysis was conducted to quantify the magnitude and direction of relationship between prior cognitive exertion and different types of physical performance tasks. Results of that analysis suggest that tasks requiring precision (i.e., motor skills) or sustained regulation of effort (i.e., aerobic, dynamic resistance, isometric resistance performance) are most sensitive to negative effects induced by prior cognitive exertion, whereas performance of tasks requiring maximal anaerobic performance such as a vertical jump, may be more resilient. Further decomposing these results to examine the influence of cognitive manipulation duration revealed similar significant negative effect sizes for manipulations lasting ≥ 30 min or < 30 min for motor and aerobic performance. The results for isometric and dynamic resistance performance revealed significant medium-sized negative effects following cognitive manipulations lasting < 30 min, whereas non-significant effects were observed for cognitive manipulations lasting ≥ 30 min. However, these findings should be interpreted with caution, as very few studies investigated isometric or dynamic resistance performance following exposure to cognitive manipulations lasting ≥ 30 min. Overall, our findings align with Pageaux and Lepers' [3] conclusions from their review of 29 studies which found performance of motor skills and tasks requiring endurance at submaximal intensities were impaired by mental fatigue, whereas tasks involving maximal anaerobic performance were unaffected.

Pageaux and Lepers [3] noted that their findings are consistent with the psychobiological model of endurance performance, which recognizes intensified perceptions of effort stemming from mental fatigue as a key intermediary variable that influences the prior cognitive exertion–physical performance relationship [80–83]. Pageaux et al. [19] have built upon the original psychobiological model [82] by proposing a potential physiological explanation why prior cognitive exertion negatively affects tasks involving prolonged effortful regulation, but not brief maximal effort tasks. They suggest that performing a demanding cognitive task leads to an accumulation of extracellular adenosine within the anterior cingulate cortex (ACC), which exacerbates perceptions of effort. For tasks requiring brief maximal anaerobic performance, conscious regulation of "all-out" effort does not require pacing, which allows individuals to endure perceptions of effort that are extremely high for very brief durations. On the contrary, for tasks requiring submaximal effort regulation over longer periods of time, intensified perceptions of effort are experienced while people are performing the task and can have negative effects on performance in two ways. That is, for fixed-demand tasks (e.g., sustaining constant force production of a percentage of one's maximum), people reach their limit of tolerable perceived exertion sooner, causing them to quit earlier than they would if they were not fatigued; for variable-demand tasks (e.g., adjusting workload to maintain a tolerable level of perceived exertion), people decrease the load to levels below that at which they would typically experience the same level of exertion in a non-fatigued state. Thus, for research investigating submaximal effort tasks, the interaction between perceived exertion and performance should be an important consideration informing researchers' choices of physical performance measures and study design.

Although there has been little theorizing about why motor performance is negatively affected following cognitive exertion, it is plausible that regulation of attentional effort plays an important role in the planning and successful execution of motor tasks. Common underlying pathways responsible for regulation of physical and attentional effort may exist; however, research is only just beginning to identify similarities across different domains (cf. Müller and Apps [84]).

Martin and colleagues [85] have since extended Pageaux et al.'s [19] model by adding a second pathway suggesting that accumulation of adenosine also leads to inhibition of dopamine release within the ACC and in turn reduces motivation to exert further effort. This psychophysiological line of theorizing merges central concepts from the two most prominent perspectives from the self-control literature that have been brought forth to explain ego depletion: resource- and motivation-based models. For instance, the strength model proposes that self-control is dependent on a central resource, which is depleted with effortful regulation, curtailing people's future ability to successfully enact self-control [9, 14]. On the other hand, the process/motivation model suggests that prior exertion of self-control leads to down-regulated effort investment in the task at hand or redirection of effort to more rewarding pursuits [86, 87]. From this standpoint, Martin et al.'s [85] psychophysiological explanation may be an appropriate model to interpret findings from the broader ego-depletion literature as well; however, this model has not been directly tested in humans and is largely based on animal research showing adenosine administration reduces effortful behavior [88–90] and adenosine accumulates with time spent awake [91]. While it is evident that cognitive exertion has detrimental effects on effort regulation, the neurophysiological pathways by which this phenomenon occurs in humans are currently unknown. Moving forward, research using human and animal models to investigate whether administering graded doses of adenosine elicits proportional effects on effortful behavior could provide insight into a complex cascade of biological processes mediating the cognitive exertion–physical performance relationship.

Although explanatory mechanisms in the mental fatigue literature have focused on putative neurophysiological pathways, there are a number of potential intermediary mechanisms that have been investigated objectively in both the self-control and fatigue literatures in relation to tasks not involving physical activity. For example, neuroimaging studies have shown that declines in performance of tasks requiring effort regulation are associated with alterations in activation patterns in brain areas responsible for effort regulation such as the ACC, anterior insula and prefrontal cortex [84, 92]. Specific to the prior cognitive exertion–physical performance relationship, evidence has shown that cognitive exertion causes alterations in brain activation patterns which are sustained during exercise performance and associated with a 2% performance decline [93].

Research employing objective neurophysiological measurements should be considered the next frontier in studies examining the relationship between prior cognitive exertion and physical performance as previous studies have primarily measured subjective perceptions prior to engaging in the physical task. Results have shown that cognitive exertion is associated with greater mental demand [59, 74, 94] and perceptions of fatigue [44, 45, 95] as well as reduced task self-efficacy [26, 58, 78], affective valence [6, 26] and intended physical exertion [27, 31, 96]. However, few studies have used statistical analysis techniques to test mediational pathways through which cognitive exertion affects physical performance [26, 58]. To better understand why and when cognitive exertion affects physical performance, researchers need to include sample sizes with adequate power to test mediational pathways. Freely accessible software such as PROCESS [97] and MEMORE [98] macros are available to do so.

4.1 Limitations

The current systematic review and meta-analysis provides the most comprehensive assessment of the prior cognitive exertion–physical performance literature to date. However, there are a number of limitations that must be considered. First, in the body of literature examined, risk of bias assessments failed to identify any study as low risk and only 10 studies were considered of some concern. Performance bias and detection bias are two of the primary factors contributing to studies being classified as high risk of bias. One way to improve upon current methodologies would be to employ double-blinding procedures. Having one experimenter deliver the cognitive manipulations and another administer the physical task will help to control any language and/or behavior that may affect the participant's cognitions and/or behavior. Second, in order to examine the overall effect of cognitive exertion on subsequent physical performance, studies involving multiple effect sizes derived from different physical tasks [22, 24, 65, 66] were combined to create a composite effect to avoid a unit-of-analysis error (i.e., double counting of participants). This procedure limited our ability to include the individual effect sizes that make up these composite effect sizes within the subgroup analysis of physical performance task type. Doing so would not have not caused major changes in the aerobic, isometric or motor performance effect sizes, although the significant decline ($d = -0.51$) in sprint performance found by Veness et al. [65] may have altered our conclusions regarding maximal anaerobic performance, which were based on only two comparisons, one of which involved a composite effect size across three maximal anaerobic tasks [61].

Another limitation is a lack of including a subgroup analysis examining participant characteristics. While it would have been interesting to discern whether trained samples' performance is less susceptible to the effects of cognitive exertion than untrained samples' performance as shown in a small number of studies [49, 50], inconsistent reporting of participant characteristics limited examination of this potential moderator. Future work investigating whether trained samples have higher resilience to the effects of cognitive exertion through learned techniques such as self-talk [99] and attentional focus would be a worthwhile avenue to pursue. Lastly, our meta-analysis focused on the direct relationship between prior cognitive exertion and physical performance. One shortcoming of this approach is that we did not account for changes in perceptions of physical exertion, a variable that has been hypothesized to indirectly affect the prior cognitive exertion–physical performance relationship [19, 85]. In studies demonstrating a null effect, this approach fails to consider that it may have felt more effortful to achieve equivalent task performance. Considering no studies have tested this theory using appropriate mediation analysis techniques, future research has the potential to provide critical insight to inform theory in this area (e.g., psychobiological model).

5 Conclusion

In conclusion, findings from 91 comparisons involving over 2500 participants showed a significant small-to-medium negative effect of prior cognitive exertion on physical performance that is stable and not attributable to random error. Subgroup analyses suggest that physical tasks involving prolonged effort regulation or motor skills are impaired, whereas findings for tasks involving maximal anaerobic performance are unclear. Cognitive effort may be more important than the duration of the task with regard to eliciting negative carryover effects. Future studies are required to better understand intermediary pathways by which psychological and physiological factors influence the prior cognitive exertion–physical performance relationship.

Data availability The dataset generated during and analyzed for the present review is available from the corresponding author on reasonable request.

Compliance with Ethical Standards

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Ethical standards Denver Brown, Jeffrey Graham, Kira Innes, Sheereen Harris, Ashley Flemington and Steven Bray declare that this systematic review and meta-analysis complies with all ethical standards.

Conflict of interest Denver Brown, Jeffrey Graham, Kira Innes, Sheereen Harris, Ashley Flemington and Steven Bray have no conflicts of interest relevant to the content of this systematic review and meta-analysis.

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