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The effect of ego depletion or mental fatigue on subsequent physical endurance performance: a meta-analysis

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Highlights

- Ego depletion and mental fatigue impair subsequent endurance performance
- The duration of the mental effort task doesn't predict the magnitude of impairment
- The effect is higher on isolation than whole-body tasks
- The effect is higher when the person-situation fit is low
- This effect should not be seen only through the "fatigue" prism but also as "value"

Abstract

Two independent lines of research propose that exertion of mental effort can impair subsequent performance due to ego depletion or mental fatigue. In this meta-analysis, we unite these research fields to facilitate a greater exchange between the two, to summarize the extant literature and to highlight open questions.

We performed a meta-analysis to quantify the effect of ego-depletion and mental fatigue on subsequent physical endurance performance (42 independent effect sizes).

We found that ego-depletion or mental fatigue leads to a reduction in subsequent physical endurance performance (ES = -0.506 [95% CI: -0.649, -0.369]) and that the duration of prior mental effort exertion did not predict the magnitude of subsequent performance impairment (r = -0.043). Further, analyses revealed that effects of prior mental exertion are more pronounced in subsequent tasks that use isolation tasks (e.g., handgrip; ES = -0.719 [-0.946, -0.493]) compared to whole-body endurance tasks (e.g. cycling; coefficient = 0.338 [0.057, 0.621]) and that the observed reduction in performance is higher when the person-situation fit is low (ES for high person-situation fit = -0.355 [-0.529, -0.181], coefficient for low person-situation fit = -0.336 [-0.599, -0.073]).

Taken together, the aggregate of the published literature on ego depletion or mental fatigue indicates that prior mental exertion is detrimental to subsequent physical endurance performance. However, this analysis also highlights several open questions regarding the effects' mechanisms and moderators. Particularly, the surprising finding that the duration of prior mental exertion seems to be unrelated to subsequent performance impairment needs to be addressed systematically.

Keywords

Self-control; cognitive fatigue; mental effort; motivation, conservation of resources

Introduction

To perform at our best, we frequently have to control ourselves and have to consciously employ mental effort in order to achieve a valued goal. For example, in order to achieve excellent grades in university, a student has to study hard and employ mental effort to ward off any internal (e.g., task-induced boredom) or external (desirable behavioural alternatives, proposed by friends) detractors of successful goal pursuit. The same holds for a cyclist who has to invest mental effort to fight off the urge of slowing down, although her body is aching. Thus, the effective self-regulation of human performance frequently hinges on the exertion of mental effort.

Despite its ubiquitous nature (or due to it), arriving at an operational definition of mental effort has been surprisingly challenging (Shenhav et al., 2017). Here, we follow the approach by Shenhav et al. (2017, p. 100), who define mental effort in terms of information processing: "Effort is what mediates between (a) the characteristics of a target task and the subject's available information-processing capacity and (b) the fidelity of the information-processing operations actually performed, as reflected in task performance." Although it refers to mental effort, this definition can also be intuitively explained with an example from physical effort. Say, a marathon runner is able to run a marathon in 02:14:00h (i.e., capacity). To qualify for the Olympics, he needs to run it in < 02:19:00h (i.e., task characteristics). Effort is what mediates between his running capacity and the required qualifying time, on the one hand, and the marathon time that is ultimately achieved. From an information processing perspective, tasks require more effort if they require the control of more default (i.e., automatic) responses (Schneider & Shiffrin, 1977). To illustrate, when a cyclist is aching, the default response would be to stop. However, to win this response needs to be controlled. Control can then be defined as the force through which mental effort is exerted (Shenhav et al., 2017).

Despite its instrumentality for achieving goals, people avoid exerting mental effort (Shenhav et al., 2017) and when mental effort is exerted, this feels aversive (Kool & Botvinick, 2014) and leads to sensations of fatigue (Wolff, Sieber, Bieleke, & Englert, 2019). Thus, mental effort appears to carry an intrinsic disutility (Kool & Botvinick, 2018) and effort is only mobilized when the goal is subjectively worth it (Gendolla & Richter, 2010). In addition, effort mobilization directly corresponds to task difficulty (Wright, Mlynski, & Carbajal, 2019), implying a restrain to mobilize effort in excess (Richter, Gendolla, & Wright, 2016). Going back to the example of the marathon runner: If the only goal is to qualify for the Olympics (i.e., no other incentives like price money or a personal record play a role), the runner should only run as fast as needed to qualify. Indeed, a large body of research has shown that people try to conserve energetic resources when it comes to the mobilization of effort (Richter et al., 2016).

Taken together, people invest mental effort sparingly and treat its' mobilization as if the capacity for control is limited (Shenhav et al., 2017). Attesting to this possible limitation, a large body of research has shown that prior exertion of mental effort impairs subsequent cognitive (Hagger, Wood, Stiff, & Chatzisarantis, 2010) and physical performance (Van Cutsem, Marcora, et al., 2017). Two largely independent lines of research in psychology and exercise physiology have postulated theoretical frameworks that account for this phenomenon (e.g., Marcora et al., 2009; Muraven et al., 1998). As expected with two independent research fields, what appears to be the same phenomenon is studied with different experimental paradigms and explained using different explanations (Pattyn, Van Cutsem, Dessy, & Mairesse, 2018). In the present paper, we want to briefly introduce the two dominant theoretical models from both fields and highlight similarities in regard to the predictions they make regarding the effect of mental effort exertion on subsequent physical performance. We will then quantify the empirical evidence for or against these predictions with a meta-analysis of the published literature.

Ego depletion

In the last two decades, the strength model of self-control (Muraven, Tice, & Baumeister, 1998) has been by far the most popular psychological model for explaining performance decrements due to the prior exertion of mental effort. According to the strength model, the capacity to exert mental effort hinges on a depletable global self-control resource (Hagger et al., 2010). The state of depleted self-control resources is called *ego depletion* and supposedly leads to impaired performance in subsequent self-control demanding tasks. This is because depleted self-control is thought to replenish only slowly and individuals have to make do with very limited resources (Muraven, Collins, Shiffman, & Paty, 2005). According to the strength model, all self-control processes draw on the same limited resource, implying that applying self-control in one task (e.g. regulating an emotional response) will affect performance in a completely unrelated self-control demanding physical task (e.g. handgrip task) (Muraven et al., 1998). Importantly, self-control can also be conceptualized as a trait (Tangney, Baumeister, & Boone, 2004) and individuals high in self-control are supposedly less prone to ego depletion (Muraven et al., 2005; but see also Lindner, Nagy, Ramos Arhuis, & Retelsdorf, 2017). In ego depletion research, the first task is usually called the primary task or the ego depletion task.

A host of research has reported support for the strength models' propositions and a meta-analysis of $k = 81$ studies has found a medium-to-large effect size of ego depletion on diverse outcome domains (e.g., impulse control, choice behaviour, volition, cognitive processing, Hagger et al., 2010). Applied to physical performance, researchers have found detrimental effects of ego depletion on choking under pressure (Englert & Bertrams, 2012), endurance (Englert & Wolff, 2015), or sprint start performance (Englert, Persaud, Oudejans, & Bertrams, 2015). For an overview on ego depletion and physical performance, please see (Englert, 2016; Englert, 2017). However, it is important to note that failures to replicate the strength models propositions have accumulated in recent years (e.g. Lurquin et al., 2016; Wolff, Sieber, et al., 2019) and a multi-lab preregistered replication report (RRR) failed to find evidence for the ego depletion effect (Hagger et al., 2016).

Mental fatigue

In exercise physiology, these performance decrements are primarily explained by a *mental fatigue* which is thought to occur after prolonged exertion of mental effort (Marcora, Staiano, & Manning, 2009). More specifically, according to the psychobiological model of endurance performance (Marcora, 2009; Marcora & Staiano, 2010), perception of effort is the 'cardinal exercise stopper' (Staiano, Bosio, Morree, Rampinini, & Marcora, 2018) and perception of effort during a physical task can be affected by – among others – prior induction of mental fatigue.

Indeed, research from cognitive neuroscience indicates that areas in the prefrontal cortex play a crucial role in the regulation of effortful control (Shenhav, Botvinick, & Cohen, 2013; Vassena, Holroyd, & Alexander, 2017). More specifically, the anterior cingulate has been linked to the sensation of effort (Williamson et al., 2001), the decision to further invest effort and heightened prefrontal cortex activation has been found when participants anticipate the need to invest mental effort (Vassena, Gerrits, Demanet, Verguts, & Siugzdaite, 2019). In line with this, prefrontal cortex activation has been found to increase as a function of the effort participants have to put into an endurance task (Wolff, Bieleke, et al., 2018; Wolff, Sch, et al., 2019). Interestingly, prior to task failure in an exhausting cycling task a drop in activation has been frequently reported (Rooks, Thom, McCully, & Dishman, 2010), which indicates that a certain level of activation in the prefrontal cortex is needed to perform an effortful task (Hosking, Cocker, & Winstanley, 2015). From the perspective of mental fatigue, this indicates that prior mental exertion leads to an accelerated increase in perception of effort which will then lead to a premature task termination (Marcora et al., 2009). (Pattyn et al., 2018)In this paradigm, the first task is often referred to as mental fatigue or cognitive fatigue task.

Research has found support for the notion that mental fatigue affects subsequent performance with a particular emphasis on endurance performance (Van Cutsem, Marcora, et al., 2017). For example, Marcora et al. (2009) found a detrimental effect of mental fatigue on subsequent cycling performance. While the published literature on mental fatigue appears to be rather consistent (but see Vrijkotte et al., 2018), it is important to note that highly cited replication failures on ego depletion stem from pre-registered studies with very large samples (e.g. Hagger et al., 2016; Lurquin et al., 2016). Such studies have not yet been conducted in mental fatigue research. We believe it will be an important next step for mental fatigue research to also use studies with bigger samples to get a better estimate of the effects' true size (Button et al., 2013).

Ego depletion and mental fatigue: how prior mental exertion affects subsequent performance

Ego depletion and mental fatigue make a strikingly similar proposition: Prior exertion of mental effort will impair endurance performance on a subsequent task and this impairment can only partly be compensated by motivation (Baumeister & Vohs, 2007; Van Cutsem, Marcora, et al., 2017). Possibly the main observable difference between research labelled as 'mental fatigue research' or 'ego depletion research' is the duration of the fatiguing (above or equal to 30 min; Van Cutsem, Marcora, et al., 2017) or depleting task (mostly less than 30 min). As Pattyn and colleagues recently stressed, the use of different terminology in the different scientific fields has led to independent streams of research, possibly inducing slower dissemination of ideas and rediscovery of 'old news' (Pattyn et al., 2018). Taking this point into account, the aim of the present paper is not to make a comparison of the relative explanatory merit between ego-depletion and mental fatigue research but to provide a data-driven discussion of the published literature in regard to key propositions made by both theories. To our knowledge, this is the first attempt at a unified synthetization of published literature on the effect of prior mental exertion on subsequent physical endurance performance. We focus on physical endurance performance, because this is a domain where both, ego depletion and mental fatigue researchers, have made sizable contributions to, thereby making the synthetization attempt worth wile. We hope that the present observations will prove helpful in locating the knowns and unknowns regarding those two similar but largely independent lines of research and to facilitate a better understanding for the way physical performance is affected by prior mental exertion.

The present study

In both lines of research, mental effort is exerted to induce a state that is then either labelled ego depletion or mental fatigue. For clarity and neutrality, we will refer to the ego depletion or the mental fatigue task as the *mental effort task* as this describes the actual behaviour (i.e., exertion of mental effort) and not an expected result of this behaviour (i.e., ego depletion or mental fatigue). As a starting point, we will assess the very premise of both models: does prior mental effort impair subsequent endurance performance? Building on this main research question, we will then meta-analyse three questions:

First, both ego-depletion and mental fatigue researchers propose that the duration of the cognitive demanding task plays an important role in the alteration of the subsequent endurance task. Regarding ego depletion, a linear association between duration of the depleting task and the size of the ego depletion effect is expected (Hagger et al., 2010). Thus, the effect should scale with time, but the model does not specify a lower limit for the duration mental effort needs to be exerted for an ego depletion effect to occur. Contrary to this, mental fatigue is only thought to reliably occur if the mental exertion was at least 30 minutes long (Van Cutsem, Marcora, et al., 2017). Interestingly, we are not aware of any research that has compared the average duration of mental effort tasks between both fields. To address this, we will compare field-dependent task durations and then assess if a longer mental effort task indeed leads to a more severe performance impairment.

Second, different types of physical endurance performance tasks pose different physiological (and possibly psychological) challenges. Endurance tasks can engage the whole body or only involve a few specific muscles (i.e., isolation task). Running or cycling are typical examples of a whole-body endurance task, whereas persistence in a handgrip task is an example of an isolation task. It is conceivable that prior mental exertion differentially affects performance as a function of task type. Indeed, single joint tasks and whole body tasks possibly use different motor modules that require different levels of automaticity, fine motor control and attention, processes which possibly interact differently with ego-depletion or mental fatigue (Boksem, Meijman, & Lorist, 2005; Englert & Bertrams, 2013; Englert, Zwemmer, Bertrams, & R. D. Oudejans, 2015). Furthermore, differences in regard to how measurements for whole body tasks (e.g. a cycling ergometer task with constant power and free cadence) and isolation tasks (e.g. isometric muscle contraction with a visual feedback requiring constant fine force adjustment in order to avoid force production in excess; Giboin et al., 11 Aug. 2018) are frequently taken can conceivably affect the attentional demand they place on a subject and thereby the mental effort they require. (Van Cutsem, Marcora, et al., 2017)In the mental fatigue field, no difference of effect was seen so far between the two types of tasks. However, the amount of mental fatigue studies performed on isolation tasks is very scarce compared to studies with whole body tasks, (Van Cutsem, Marcora, et al., 2017). To address this, we will test if mental exertion differentially impairs performance in whole-body and isolation endurance tasks.

Third, both the ego depletion and the mental fatigue fields conceptualize the detrimental effect of mental exertion as some form of transient 'fatigue' (Pattyn et al., 2018). However, while longer exertion of mental effort can cause higher levels of perceived fatigue, this must not lead to impaired performance (Wolff, Sieber, et al., 2019). Accordingly, researchers have cautioned against the implication that such fatigue must reflect some form of resource depletion (Inzlicht & Marcora, 2016) and have instead emphasized the importance of motivational processes (Inzlicht, Schmeichel, & Macrae, 2014). Indeed, there might even be instances where exertion of physical effort is perceived as valuable, despite its apparent costs (Inzlicht, Shenhav, & Olivola, 2018). In the same vein, if a persons' personal preferences align with the task-induced demands, then this task should incur less costs per unit of time (Gropel & Kehr, 2014; Kehr, 2004; Kuhl, 2001) and might even be enjoyable (Brunstein, Schultheiss, & Grassmann, 1998). Put in the context of the current paper, if a recreational cyclist is asked to perform a cycling task, the fit between the person and the situation is supposedly higher than when a non-cyclist is asked to do the same. Thus, we expect the detrimental effect of prior mental effort exertion to be lower when person-situation fit is high, compared to when it is low.

Methods

We performed a meta-analysis of the effect of prior mental exertion on subsequent endurance performance. We searched for publications on Pubmed, with the keywords "mental fatigue" OR "cognitive fatigue" AND "exercise, performance, physical" (310 hits, end of April 2019), and "ego depletion" OR "self-control" AND "exercise, performance, physical" (1012 hits, end of April 2019). Additionally, we performed reverse citation search to increase the probability of relevant article detection. Only original studies written in English were screened. We screened publications according to title and abstract. The study selection process is resumed in Figure 1 (PRISMA Flowchart, Moher, Liberati, Tetzlaff, Altman, & The, 2009). As our focus was on physical endurance performance, we included studies where the performance outcome was whole body or single joint or single limb endurance task, and excluded studies where skill-based physical tasks were used as dependent tasks (e.g. shooting accuracy). We integrated between group and cross-over studies (with wash out phase of at least one day between the 2 conditions for the latter type of studies). Since cross over and between groups designs are problematic to integrate together, we followed the advice of the Cochrane Handbook for meta-analysis and calculated Cohen's *d* as if all studies had parallel groups (mean group difference in performance post demanding cognitive task divided by the pooled standard deviation) (J. Higgins & Green, 2011). For the relevant studies using handgrip tasks, the effect size was calculated following the design of these studies, i.e. calculated with the difference of performance before and after the psychological intervention. For one study, we calculated Glass' delta since the SD of the intervention group was not displayed in the paper. For 2 studies we calculated the effect size according to the F values, and in 2 studies, the appropriate effect size was already displayed. Four studies were excluded due to the particular statistics model used and/or lack of descriptive statistics that prevented effect size calculation. One of the reviewers kindly indicated to us one study we missed, and which has been now included in the meta-analysis. We ended up using 42 independent effect size for analysis (see Table 1). We used JASP (Team, 2019) to perform the meta-analysis and used models with random effects and restricted maximum likelihood estimator. We used models with random effects because we estimated that the selected studies differed in their design, participants and interventions, which implies that these studies may not all share the same *true* effect size (Borenstein, Hedges, Higgins, & Rothstein, 2010). The proportion of variation in the estimate of treatment effect due to the heterogeneity between studies rather than sampling errors was estimated with I^2 (J. P. Higgins & Thompson, 2002). We performed a regression test for funnel plot asymmetry to assess bias in the meta-analysis. In the present study, a negative effect size indicates that the intervention group had a lower endurance performance than the control group, suggesting an effect from mental effort exertion on subsequent endurance performance. To assess bias in the included studies, we performed 'quality assessment' using the NIH Study Quality Assessment Tools for Controlled Intervention Studies (https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools). The criteria 9 and 10, relative to the intervention adherence and to background treatments, were not relevant for the present studies and thus not included. Assessment is displayed in Table 2.

Results and Discussion

Ego depletion or mental fatigue leads to impaired endurance performance

As displayed in Figure 2A, the random effects model summary for the average effect of mental effort on subsequent endurance performance was -0.506 [CI 95%: -0.649, -0.362] ($p < 0.001$, with $k = 42$ independent effect sizes). This result suggests that prior mental exertion indeed impairs the performance of a subsequent physical endurance task by around half a standard deviation, which corresponds conventionally to a medium effect (Leppink, O'Sullivan, & Winston, 2016). A difference of half a standard deviation in performance could bear serious implications in the world of athletic performance or clinical settings. A moderate between study heterogeneity in treatment effect was noted, indicating that the effect of the mental effort task may vary depending on some experimental factors (I^2 (%) = 40.62 [17.87, 70.74], $\tau^2 = 0.086$ [0.027, 0.304]; J. P. T. Higgins, Thompson, Deeks, & Altman, 2003). The regression test for funnel plot asymmetry was not significant ($z = -1.09$, $p = 0.27$, see Figure 2B), indicating no apparent bias in the studies included. However, it is important to remember that this test has low power and publication bias cannot be excluded (J. Higgins & Green, 2011). This is an important result for the field, since the only meta-analysis performed on the effect of mental fatigue was performed with only $k = 11$ effect sizes (McMorris, Barwood, Hale, Dicks, & Corbett, 2018) and since the very existence of the ego-depletion effect has been questioned recently (Hagger et al., 2016).

Task duration is not associated with the magnitude of performance impairment

In the studies analysed here, ego depletion tasks were substantially shorter (5.37 ± 3 min [$k = 12$, duration not given in 2 studies]) than mental fatigue tasks which lasted on average 50.25 ± 27.57 min ($k = 28$). Thus, the temporal properties of the experimental approaches of both fields align well with the different emphasis ego depletion and mental fatigue researcher place on the duration of the mental effort task.

To assess whether task duration is associated with the magnitude of subsequent performance decrement, we tested the correlation between duration of prior mental effort exertion and subsequent endurance performance and did find no significant relationship, Pearson's $r = -0.043$, $p = 0.792$ (see Figure 3). This indicates that mental effort task duration is less important than expected by either ego depletion researchers or mental fatigue researchers. While this finding is somewhat surprising, it is in line with a recent high-powered study that experimentally varied the duration of the depletion task and also did not find a relationship between duration and subsequent cognitive performance (Wolff, Sieber, et al., 2019). However, it is important to note, that the physical tasks used to assess the effect of prior exertion of mental effort also differ in length, which might influence this result. In general, the physical tasks used in the mental fatigue field are much longer than the tasks used in the ego-depletion field (947 ± 775 s versus 233 ± 329 s, respectively). This is an important point to consider since mental fatigue researchers stress that the effects of mental fatigue are more pronounced for longer physical endurance tasks (Van Cutsem, Marcora, et al., 2017). As we did not find a correlation between the physical task duration and the resulting effect size (r = 0.261, p= 0.125), this claim surely needs further investigation in the future. In conclusion, the present result seems to contrast with the theories behind ego-depletion and mental fatigue. Therefore, it appears important that researchers from both fields specifically test this effect with large samples and preferably with pre-registered studies that vary the duration of the mental effort and endurance tasks.

Performance is differentially affected in whole-body and isolation endurance tasks

To test whether the observed performance impairment varies as a function of task type, we separated the physical tasks in two categories: whole body tasks (e.g. cycling) and isolation tasks (e.g. hand-grip). We then performed a new meta-analysis with task category as factor. We found that the intercept (i.e. isolation task) was -0.719 [-0.946, -0.493] ($p < 0.001$), and the coefficient of whole-body task was 0.338 [0.054, 0.621] ($p = 0.019$), $I^2 = 33.8$ %. This result supports the idea that the effect of a demanding cognitive task on subsequent endurance performance depends on the kind of physical task used. Interestingly, isolation tasks seem to be more sensitive to the demanding cognitive task than whole body tasks. This result could potentially be explained by the fact that whole body tasks, such as cycling, might be primarily controlled by automatic motor processes (possibly through central pattern generators (Dimitrijevic, Gerasimenko, & Pinter, 1998), compared to fine single joint tasks, such as a handgrip task, where the high precision of the intrinsic hand muscles is mostly explained by the high proportion of direct corticospinal projection (Courtine et al., 2007). Thus, whole body tasks like cycling might require less attentional control for effective task execution than fine single joint tasks. It could be proposed that the more a motor control process is automatic, and the less it will be impaired by previous mental effort. This proposition is supported by the deleterious effect of ego depletion and mental fatigue on cognitive performance (Boksem et al., 2005; Englert, Zwemmer, et al., 2015). (Van Cutsem, Marcora, et al., 2017)Furthermore, differences in regard to how measurements for whole body tasks (e.g. a cycling ergometer task with constant power and free cadence) and isolation tasks (e.g. isometric muscle contraction with a visual feedback requiring constant fine force adjustment in order to avoid force production in excess; (Giboin et al., 11 Aug. 2018) are frequently taken can conceivably affect the attentional demand they place on a subject and thereby the mental effort they require. In conclusion, although this result must be carefully apprehended, since confounding factors may be at play (e.g. different mental effort and physical tasks duration), our data suggest that there might be a task-specific effect..

Less performance impairment when person-situation fit is supposedly higher

To test whether the observed performance impairment varies as a function of person-situation fit, we have separated the physical tasks in two categories: low person-situation fit (e.g. sedentary students performing a cycling task) and high person-situation fit (e.g., cyclists performing a cycling task, see Table 2). The meta-analysis with this category as a factor returned an intercept (high person-situation fit) of -0.355 [-0.529, -0.1814] ($p < 0.001$) and a coefficient for the low person-situation fit of -0.336 [-0.599, -0.073] ($p = 0.012$), $I^2 = 28.4$ %. Thus, when person-situation fit was high, the detrimental effect of prior mental effort is smaller. Of course, one should be aware of the fact that this is a post-hoc categorization. A study specifically designed to test this effect is definitely required. Nevertheless, these results indicate that mental effort-induced performance decrements should not solely be considered through the prism of 'fatigue' (Pattyn et al., 2018), but also within the prism of 'value'. Recent years have seen a surge in value-based conceptualizations of this phenomenon (Shenhav et al., 2017; Wolff, Sieber, et al., 2019). For example, Job et al., showed that whether or not individuals were prone to ego depletion depended on their own implicit theories regarding the limits of self-control (2010) (Job, Dweck, & Walton, 2010): If self-control was conceived as unlimited, no ego depletion effect was observed. Francis and Job (Francis & Job, 2018) (2018) suggest that such implicit theories "affect how mental work is processed […] [and] might change the expected value of a self-control task, including its feasibility and desirability (p. 8)." We believe that research on ego depletion and mental fatigue would greatly benefit from tackling this phenomenon from such a more motivational, value-based standpoint. Theoretical frameworks like the process model (Inzlicht *et al.*, 2014), the mental labour theory (Kool & Botvinick, 2018), the expected value of control (Shenhav et al., 2013; Shenhav, Cohen, & Botvinick, 2016) or the model of value based choice of self-control (Berkman, Hutcherson, Livingston, Kahn, & Inzlicht, 2017) could be utilized to facilitate our understanding of how mental effort is allocated and is linked to subsequent performance.

Limitations

We advise our readers to consider the present results with care due to the limitations inherent to the research questions we attempted to answer with the present meta-analysis. Indeed, the quantitative analysis presented here only rests on published literature and we have not searched for conference papers and have not contacted research teams about unpublished data sets. We are well aware of the possibility that we might have missed unpublished studies on the topic. A recent survey among ego depletion researchers showed that ca. two out of five ego depletion studies are not published which points to the existence of a substantial body of grey literature (Wolff, Baumann, & Englert, 2018). It must be noted however that leading groups in the mental fatigue and ego depletion field do not hesitate to publish negative results, e.g. (Hagger et al., 2016; Martin et al., 2016; van Cutsem, de Pauw, et al., 2017). We chose to only meta-analyse the literature that fellow researchers can also readily assess and likely base their research questions on. This synthesis can then serve as a starting point for an ever-growing synthesis of the available evidence and should ideally be developed into a 'living review' (Elliot et al., 2014).

Moreover, we have used the same effect size calculation for both between groups and cross-over studies (J. Higgins & Green, 2011; Morris & DeShon, 2002). We have also not hierarchized the included studies according to their methodological qualities. According to the studies quality assessment, bias may arise mostly from differences in the blinding to interventions, and to the selection of sample size not adequate to estimate the *true* effect. It is also important to acknowledge that within each field, and between fields, the experimental designs differ, and the effect of the treatment is not measured with the same metrics (due to the diverse tasks tested and the diverse experimental protocols). As such, the standardized effect sizes obtained does not guarantee a comparison on the same metrics (Morris & DeShon, 2002). These differences also increase the probability that the meta-analysis and correlation results might be spurious or masked by cofounding factors. Obviously, the present results need to be backed up by a large sample original study that specifically test the present outcomes. Being in favour of open science and transparency, we invite the readers to download the data used to construct the present meta-analysis and apply different statistical corrections to help confirm or infirm the present results (https://figshare.com/articles/The_effect_of_ego_depletion_or_mental_fatigue_on_subsequent_physical_endurance_performance_A_commentary_and_meta-analysis/9255425).

Making this work a 'living review'

The effect of ego-depletion and mental fatigue on subsequent physical performance is definitely a hot topic, and a fast changing field. Due to the rapid rate of publication in both fields, the present review may soon become obsolete (Elliott et al., 2014). Therefore, with an open-science perspective, we invite the readers to download and update the present results with studies we have not been able to find, with 'file drawer' studies and with future published work to share them to the community on a public repository or in publications.

Conclusions

In this paper, we have summarized the theoretical underpinnings of two lines of research that have evolved largely independent from each other in psychology (ego depletion) and in exercise physiology (mental fatigue) and that both aim at explaining the apparent reduction in (physical) performance after prior mental exertion. We have conducted the most comprehensive meta-analytic summary (k = 42 independent effect sizes) on this phenomenon and on its' potential moderating factors so far. We found a medium sized effect showing that prior exertion of mental effort indeed leads to subsequent decrements in physical endurance performance. Tasks that are aimed to induce ego depletion are substantially shorter than those aimed at causing mental fatigue. However, correlational analyses revealed that observed decrements in endurance performance were independent of task duration. Thus, mental effort task duration did not matter. To outline two further questions for future research, we have found that ego depletion or mental fatigue is more detrimental to performance in subsequent isolation tasks (e.g., handgrip) compared to whole-body endurance tasks (e.g., cycling) and that performance suffers more when the physical endurance task is of low person-situation fit (e.g., non-cyclists performing a cycling task) compared to when it is of high person-situation fit (e.g., cyclists performing a cycling task). Different psychological and physiological task properties possibly contribute to the former, whereas the latter underlines the need to also take motivational aspects into account when trying to understand the mental effort – physical performance relationship. We encourage fellow researchers to systematically investigate these findings and we hope that the present paper contributes to psychologists and exercise physiologists joint efforts to advance our understanding of this phenomenon.

Data statement

Please download the data used for the present meta-analysis here:

https://figshare.com/articles/The_effect_of_ego_depletion_or_mental_fatigue_on_subsequent_physical_endurance_performance_A_commentary_and_meta-analysis/9255425

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Figures and tables

Table

Publication	Design	Cognitive task	Cognitive task duration	Subjects	N	N (control)	Person situation fit	Physical task
Clark et al., 2019, (Clark et al., 2019) exp 1	cross over	stroop task and 1-back task	30	competitive male athletes	10		high	cycling CWRTT
Clark et al., 2019, (Clark et al., 2019) exp 2	cross over	stroop task and 1-back task	30	healthy male untrained	10		low	cycling CWRTT
Graham et al., 2018 (Graham, Li, Bray, & Cairney, 2018)	between groups	stroop task	5	children	37	33	low	handgrip task TTE
Staiano et al., 2018 (Staiano, Bosio, Piazza, Romagnoli, & Invernizzi, 2018)	cross over	stroop task	60	under 17 elite kayakers	13		high	2000 m kayaking TT
Salam et al., 2018 (Salam, Marcora, & Hopker, 2018)	cross over	stroop task	30	well trained male cyclists	11		high	cycling TTE
Slimani et al., 2018 (Slimani, Znazen, Bragazzi, Zguira, & Tod, 2018)	cross over	stroop task	30	adolescent endurance athletes	10		high	incremental running shuttle test
Vrijkotte et al., 2018 (Vrijkotte et al., 2018)	cross over	stroop task	90	adults trained cyclists	9		high	incremental cycling test
Silva-Cavalcante et al., 2018 (Silva-Cavalcante et al., 2018)	cross over	AX-CPT	90	male adults road cyclists	8		high	4 km cycling TT
Brown et al., 2018 (Brown & Bray, 2018)	cross over	AX-CPT	50	unfit university students	25		low	30 min self-paced cycling ergometer
Filipas et al., 2018 (Filipas, Mottola, Tagliabue, & La Torre, 2018)	cross over	Stroop task	60	young rowers	17		high	1500 m rowing TT
Pires et al., 2018 (Pires et al., 2018)	cross over	Rapid Visual Information Processing	30	recreational cyclists	8		high	20 km TT
Ferris et al., 2018 (Ferris, Tomlinson, Ward, Pepin, & Malek, 2018)	cross over	AX-CPT	60	healthy college student	8		low	knee extension kicking
Brown et al., 2017 (Brown & Bray, 2017)	between groups	stroop task	10	recreational active university student	20	21	low	hand grip TTE
Penna et al., 2017 (Penna et al., 2018)	cross over	stroop task	30	adolescent competitive swimmers	16		high	1500m swimming TT
Van Cutsem et al., 2017 (van Cutsem, de Pauw, et al., 2017)	cross over	stroop task	45	trained mal athletes or triathletes	10		high	45 min fixed cycling workload + self-paced TT
Boat & Taylor, 2017 (Boat & Taylor, 2017)	cross over	stroop task	4	recreationally active young adults	63		high	wall sit
Zering et al., 2017 (Zering, Brown, Graham, & Bray, 2017)	cross over	stop-signal task	10.5	untrained recreationally active university students	15		low	cycling ramp test
Head et al., 2016 (Head et al., 2016)	cross over	vigilance task	52	volunteers from local gyms	18		high	bodyweight exercises for 20 min
Azevedo et al., 2016 (Azevedo, Silva-Cavalcante, Gualano, Lima-Silva, & Bertuzzi, 2016)	cross over	AX-CPT	90	male subjects familiarized with exhaustive exercise	8		low	cycling constant workload test
Martin et al., 2016 (Martin et al., 2016) exp 1	cross over	stroop task	30	pro cyclists	11		high	20 min cycling TT
Martin et al., 2016 (Martin et al., 2016) exp 2	cross over	stroop task	30	recreational road cyclists	9		high	20 min cycling TT
Smith et al., 2016 (Smith et al., 2016)	cross over	stroop task	30	male soccer players	12		high	Yo-Yo IR1 running task
Schücker & MacMahon, 2016, (Schücker & MacMahon, 2016) exp 1	cross over	stroop task	10	endurance athletes	11		high	20 m shuttle run
Schücker & MacMahon, 2016, (Schücker & MacMahon, 2016) exp 2	cross over	stroop task	10	endurance athletes	14		high	20 m shuttle run
Graham et al., 2015 (Graham & Bray, 2015)	between groups	stroop task and 1-back task	5	untrained university students	19	18	low	handgrip task TTE

Martin et al., 2015 (Martin, Thompson, Keegan, Ball, & Rattray, 2015)	cross over	AX-CPT	90	participants involved in high-intensity training	12		high	3 min cycling test
Shortz et al., 2015 (Shortz, Pickens, Zheng, & Mehta, 2015)	cross over	stroop task and 1-back task	60	old from the local community	11		low	hand grip TTE
MacMahon et al., 2014 (MacMahon, Schucker, Hagemann, & Strauss, 2014)	cross over	AX-CPT	60	young recreationally runners	20		high	3000 m run
Wagstaff,, 2014 (Wagstaff, 2014)	Cross over	Emotion suppression	3	Endurance athletes	19		high	Cycling 10 km
Pageaux et al., 2014 (Pageaux, Lepers, Dietz, & Marcora, 2014)	cross over	stroop task	30	moderately endurance trained adults	12		high	5km running TT
Graham et al., 2014 (Graham, Sonne, & Bray, 2014)	between groups	mental imagery	3	university students	25	25	low	handgrip task TTE
Brownsberger et al., 2013 (Brownsberger, Edwards, Crowther, & Cottrell, 2013)	cross over	continuous cognitive task	90	regular exercisers	12		high	cycling at given RPE
Pageaux et al., 2013 (Pageaux, Marcora, & Lepers, 2013)	cross over	AX-CPT	90	physically active male adults	10		low	isometric knee contraction
Dorris et al., 2012, (Dorris, Power, & Kenefick, 2012) exp 1	cross over	arithmetic and balance task		university sports practicionners	24		high	press ups
Dorris et al., 2012, (Dorris et al., 2012) exp 2	cross over	arithmetic and balance task		university sports practicionners	24		high	sit-ups
Bray et al., 2011 (Bray, Martin Ginis, & Woodgate, 2011)	between groups	stroop	3.66	older adults	33	28	low	handgrip task TTE
Martin Ginis & Bray, 2010 (Martin Ginis & Bray, 2010)	between groups	stroop task	3.66	non physically active university students	31	30	low	10 min cycling
Marcora et al., 2009 (S. M. Marcora et al., 2009)	cross over	AX-CPT	90	endurance trained subjects	16		high	cycling test TTE
Bray et al., 2008 (Bray, Martin Ginis, Hicks, & Woodgate, 2008)	between groups	stroop task	3.66	sedentary university students	26	23	low	hand grip TTE
Alberts et al., 2007, (Alberts, Martijn, Greb, Merckelbach, & de Vries, 2007) exp 1	between groups	labyrinths	10	university students	20	20	low	hand grip TTE
Alberts et al., 2007, (Alberts et al., 2007) exp 2	between groups	labyrinths	10	university students	20	20	low	hand grip TTE
Ciarocco et al., 2001, (Ciarocco, Sommer, & Baumeister, 2001) exp 2	between groups	confederate interaction	3	university students	12	12	low	hand grip TTE

Table 1

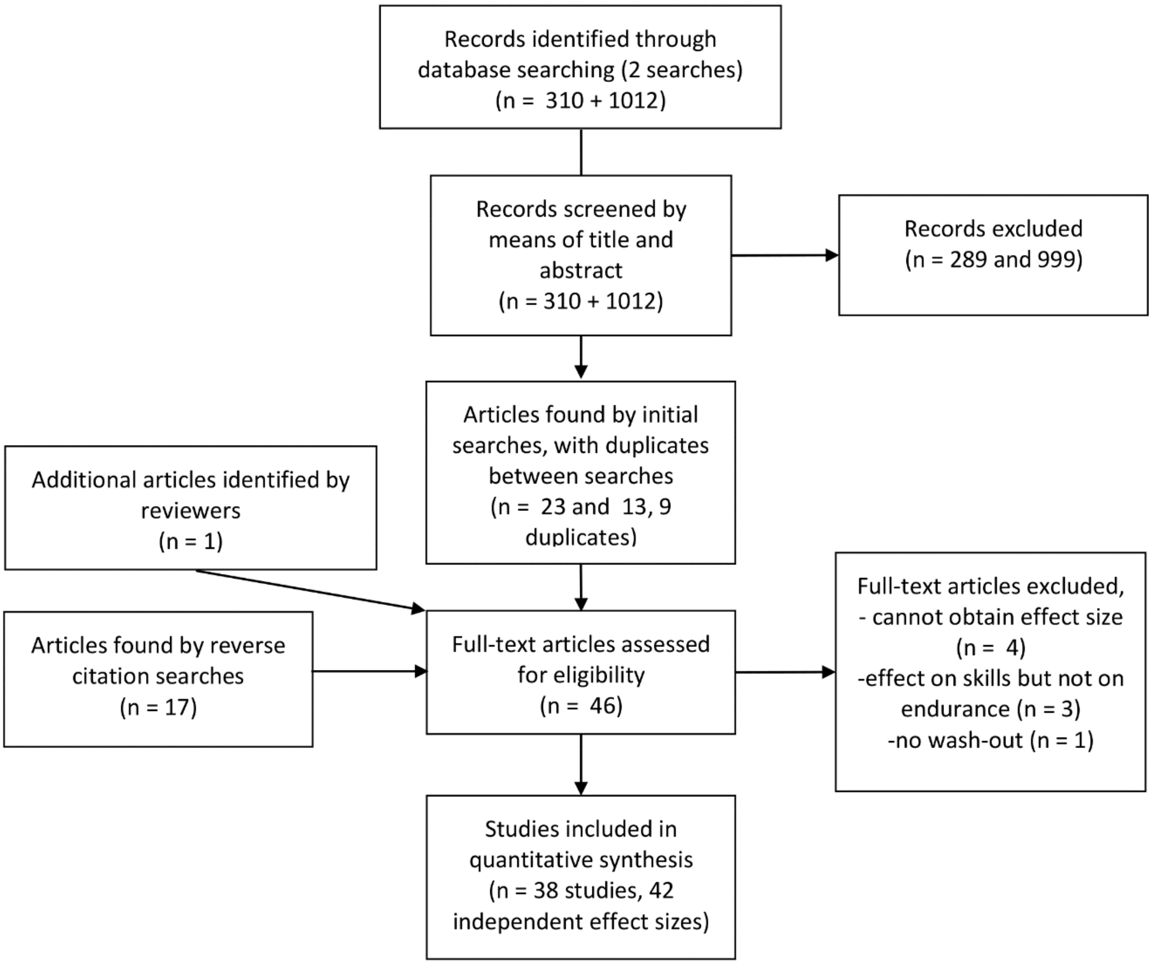
Publications details. For each trial, here are reported the trial design, the number of subjects per trial (in the case of between group design, N refers to the number of subjects in the intervention group), the type of subject population tested, the type of demanding cognitive task used and its duration (in minutes), the detail of the physical task tested and the task value attributed to the endurance task.

Table 2

Criteria	1	2	3	4	5	6	7	8	11	12	13
Clark et al., 2019	y	nr	nr	n	n	y	y	y	y	n	y
Graham et al., 2018	y	nr	nr	subjects blinded to the real aim	n	n	y	y	y	y	y
Staiano et al., 2018	y	y	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Salam et al., 2018	y	nr	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Slimani et al., 2018	y	y	nr	n	n	y	y	y	y	y	y
Vrijkotte et al., 2018	y	nr	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Silva-Cavalcante et al., 2018	n	n	n	n	n	y	y	y	y	y	y
Brown et al., 2018	n	n	n	n	n	y	y	y	y	y	y
Filipas et al., 2018	y	y	n	subjects blinded to the real aim	n	y	y	y	y	y	y
Pires et al., 2018	y	n	n	n	n	y	y	y	y	n	y
Ferris et al., 2018	n	n	n	n	n	y	y	y	y	y	y
Brown et al., 2017	y	nr	nr	subjects blinded to the real aim	n	nr	y	y	y	y	y
Penna et al., 2017	y	nr	nr	n	n	y	y	y	y	n	y
Van Cutsem et al., 2017	y	y	nr	n	n	y	y	y	y	n	y
Boat & Taylor, 2017	n	n	n	n	n	y	y	y	y	y	y
Zering et al., 2017	y	nr	nr	n	n	y	y	y	y	n	y
Head et al., 2016	y	nr	nr	n	n	y	y	y	y	n	y
Azevedo et al., 2016	y	y	nr	subjects blinded to the real aim	y	y	y	y	y	n	y
Martin et al., 2016	y	y	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Smith et al., 2016	y	y	nr	subjects blinded to the real aim	y	y	y	y	y	n	y
Schücker & MacMahon, 2016	y	nr	nr	n	n	y	y	y	y	y	y
Graham et al., 2015	y	y	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Martin et al., 2015	y	y	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Shortz et al., 2015	n	n	n	n	n	y	y	y	y	n	y
MacMahon et al., 2014	y	nr	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Wagstaff, 2014	y	n	n	subjects blinded to the real aim	n	y	y	y	y	y	y
Pageaux et al., 2014	y	nr	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Graham et al., 2014	y	y	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Brownsberger et al., 2013	y	nr	nr	n	n	y	y	y	y	n	y
Pageaux et al., 2013	y	nr	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Dorris et al., 2012	y	nr	nr	n	n	y	y	y	y	n	y
Bray et al., 2011	y	nr	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Martin Ginis & Bray, 2010	y	nr	nr	subjects blinded to the real aim	n	y	y	y	y	y	y
Marcora et al., 2009	y	y	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Bray et al., 2008	y	nr	nr	subjects blinded to the real aim	n	y	y	y	y	n	y
Alberts et al., 2007	y	nr	nr	n	n	n	y	y	y	n	y
Ciarocco et al., 2001	y	nr	nr	subjects blinded to the real aim	n	y	y	y	y	n	y

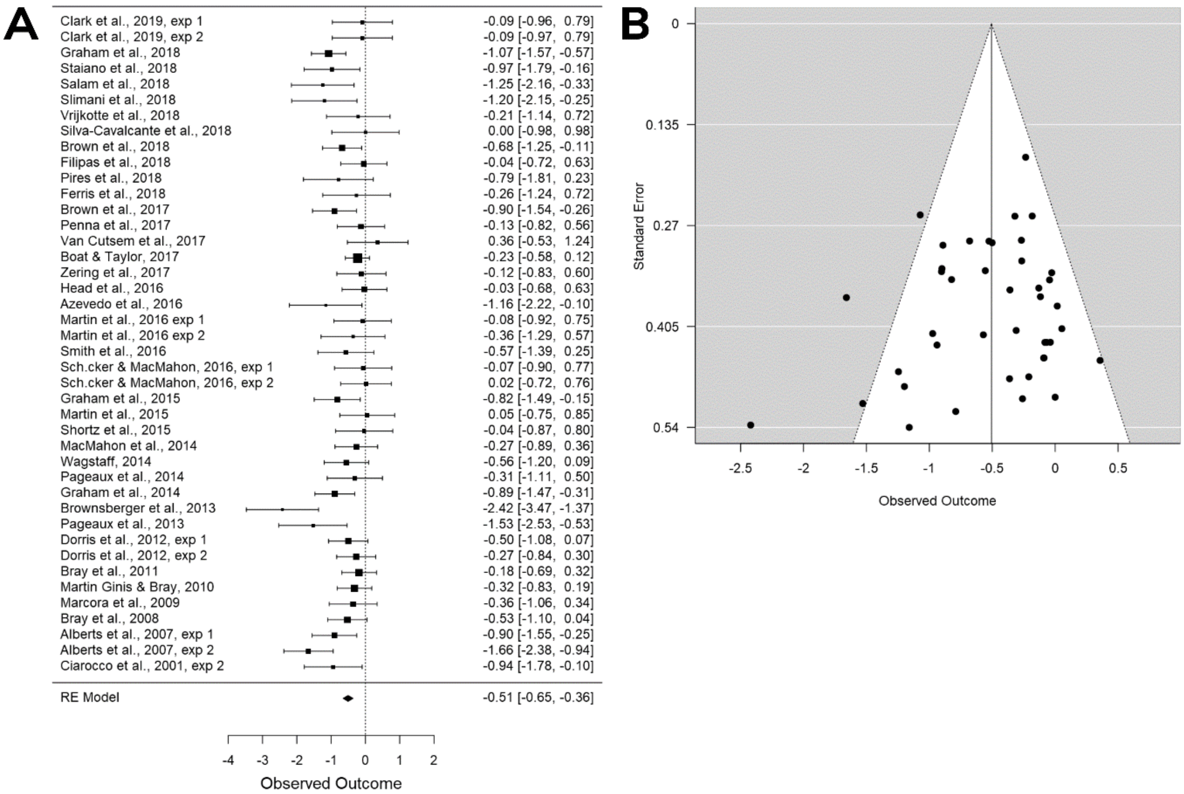
Study Quality Assessment. For more details, see https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools. Y: yes, n: no, nr: not reported. The criteria are: 1. Was the study described as randomized, a randomized trial, a randomized clinical trial, or an RCT? 2. Was the method of randomization adequate (i.e., use of randomly generated assignment)? 3. Was the treatment allocation concealed (so that assignments could not be predicted)? 4. Were study participants and providers blinded to treatment group assignment? 5. Were the people assessing the outcomes blinded to the participants' group assignments? 6. Were the groups similar at baseline on important characteristics that could affect outcomes (e.g., demographics, risk factors, co-morbid conditions)? 7. Was the overall drop-out rate from the study at endpoint 20% or lower of the number allocated to treatment? 8. Was the differential drop-out rate (between treatment groups) at endpoint 15 percentage points or lower? 11. Were outcomes assessed using valid and reliable measures, implemented consistently across all study participants? 12. Did the authors report that the sample size was sufficiently large to be able to detect a difference in the main outcome between groups with at least 80% power? 13. Were outcomes reported or subgroups analyzed prespecified (i.e., identified before analyses were conducted)?

Figure 1



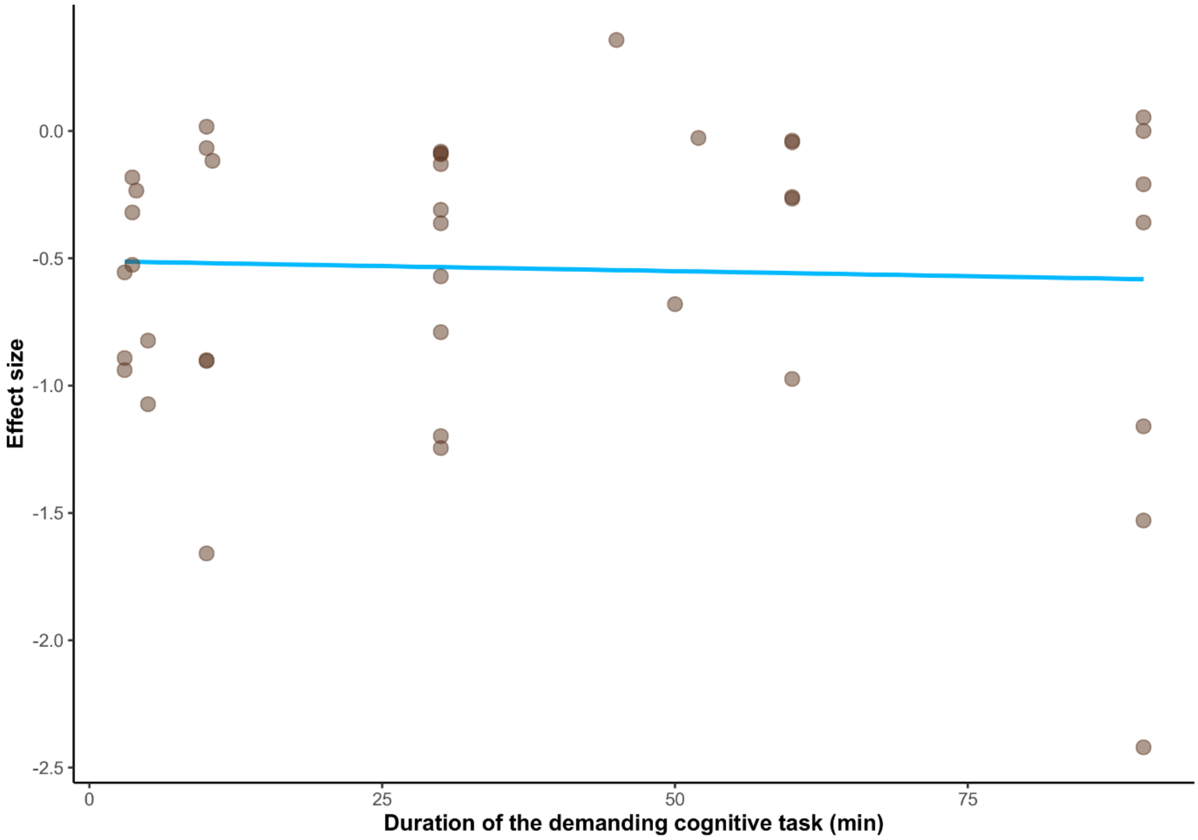
Study selection flowchart. Adapted from PRISMA (Moher et al., 2009).

Figure 2



Effect of demanding cognitive task on subsequent endurance performance. A) Forest plot. Each mark corresponds to individual trial effect size, and its size corresponds to the weight of the trial in determining the combined effect size estimate. The whiskers correspond to 95% confidence interval. The diamond shape corresponds to the combined effect size, and its width indicates the 95% confidence interval of the estimate. B) Funnel plot.

Figure 3



Correlation between effect size and the duration of the demanding cognitive task. Each point represents an effect size and the straight line represents the linear regression.