Mental fatigue might be not so bad for exercise performance after all: a systematic review and bias-sensitive meta-analysis.

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Abstract

Objective: To examine the influence of mental fatigue on exercise performance.

Design: Pre-registered (CRD42019123250) systematic review and bias-sensitive meta-analysis.

Data Sources: A systematic literature search of electronic databases (PubMed, Web of Science and Scopus) and reference lists of included articles up to April 2019.

Eligibility Criteria: Published articles in peer-review journals, randomized controlled trial comparing the effect of a cognitive task longer than 30 minutes with a neutral activity providing data on exercise performance and/or rating of perceived exertion (RPE).

Results: The initial search provided 1,917 articles of which 69 were assessed for eligibility. Finally, the analysis of effect sizes comprised 22 studies with 318 participants. The analysis indicated that the bias-corrected effect was not significantly different from zero for both the effect of mental fatigue on exercise performance d_z = 0.11, 95% CI [-0.22, 0.43] (biased effect of d_z = 0.48, 95% 95% CI [0.23, 0.73], z = 3.72, p = 0.0002) and RPE d_z = 0.20, 95% CI [-0.20, 0.60] (biased effect of 0.29, 95% CI [0.05, 0.54].

Conclusion: The current evidence is insufficient to support the conclusion that mental fatigue has a negative influence on exercise performance. The biased effect and the mixed literature do not allow us to draw firm conclusions. Future studies in this area should guarantee sound scientific practices.

Citation

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Introduction

Exercise can be viewed as complex goal-directed behaviour that involves bottom-up and top-down processing [1,2]. Exercise requires controlling and monitoring afferent feedback from the muscular and cardiopulmonary systems to the brain, which can affect effort regulation directly or indirectly. For example, in order to achieve their goals, athletes must inhibit the urge to stop or reduce exercise intensity, despite the growing feeling of fatigue or pain [3,4]. If one considers that people have limited cognitive resources, when these are depleted in one task, performance in a subsequent task demanding similar resources will be impaired [5,6]. In view of the cognitive demands imposed by physical exercise, performance in a long and demanding cognitive task (e.g., inhibitory control, cognitive control task) prior to exercise would be expected to reduce exercise capacity due to an induced state of mental or cognitive fatigue [7].

Mental fatigue[1] has been defined as a complex psychobiological state induced by a prolonged period of demanding cognitive activity, which normally impairs cognitive function and has a negative impact upon a range of subjective and objective measures of performance [9]. Mental fatigue can be experienced physiologically, subjectively and behaviourally [7]. Altered parasympathetic [10] and brain activity [11,12], lack of energy [13] and decreased response accuracy [14], among others, are some of the consequences of mental fatigue. In the context of sports, it has been proposed that performing a long cognitive task might deplete internal resources, impairing subsequent endurance [7]. An illustrative example of the negative effects of mental fatigue on exercise is a study by Marcora et al. in 2009 [15]. After completing a demanding cognitive task (AX-CPT) for 90 minutes in the mental fatigue condition, participants reached exhaustion sooner (in a cycling test at 80% of their peak power output) than in the control condition (watching two TV documentaries). Interestingly, motivation or rating of perceived exertion (RPE) did not change as a result of mental fatigue. Over the last few years, this literature has grown considerably, with some studies showing negative effects of mental fatigue [16–18] and others failing to replicate this finding [19,20]. Still, several issues in this literature deserve closer examination.

First, a recent review by Pageaux and Lepers [8] suggests that almost 50 percent of the studies report no effects of mental fatigue on exercise performance variables. Second, most studies in this literature are based on small samples (mean N = 12), which renders them underpowered to detect small but non-trivial effect sizes. Third, the effects of mental fatigue on exercise might be influenced by a series of moderators, such as the type of physical exercise and cognitive task, whose impact has not been

[1] Some authors have referred this state as a cognitive fatigue rather than mental fatigue, but, as in previous reviews, we will not make differences between terms “mental fatigue” and “cognitive fatigue”, and we will use mental fatigue consistently [7,8].

explored systematically. Finally, previous published meta-analyses on the effect of cognitive fatigue on exercise only included eight studies and it might be bias in the literature [21].

The purpose of the present meta-analysis is to shed light on whether there is a true negative effect of mental fatigue on exercise performance, given the growing interest in this area. Provided that mental fatigue might have a different impact on exercise performance and RPE, we also analysed these outcomes separately. Moreover, this study aims to contribute to this growing area of research by exploring several factors which might moderate the effects of mental fatigue on exercise, such as the type of exercise and participants, or the type and duration of the cognitive task, among others.

Methods

Pre-registration

The methods and planned analyses of this systematic review and meta-analysis were preregistered at PROSPERO (ref. CRD42019123250). All departures from the preregistered protocol are disclosed explicitly in the following sections.

Literature Search

We used the PRISMA statement [22] as the basis for the procedures described herein. We carried out a literature search on 6 April, 2019 in Medline, Scopus and Web of Science using the following terms and Boolean operators: ("mental fatigue" or "cognitive fatigue" or "mental exertion" or "ego-depletion") AND ("physical performance" or "exercise" or "muscle fatigue" or "sport" "or "RPE"). Searches were limited to papers published in English until April 2019. The reference lists of the retrieved studies were also reviewed to find additional studies that might not have appeared in the databases with our search terms.

Inclusion and Exclusion Criteria

We considered for review any study meeting the following inclusion criteria: 1) available in English; 2) controlled trials; 3) participants completed a cognitive task of 30 minutes or longer prior to a physical exercise; 4) the main outcome was a measure of exercise performance or perceived exertion during exercise (RPE). Among the exercise performance measures, we considered: time to exhaustion in a physical test (in seconds or minutes; distance completed), time-trial performance (in seconds or minutes; average power output; average speed), total work done, number of repetitions. Studies were excluded following these criteria: 1) participants were symptomatic or in poor health condition; 2) studies employed a cognitive task shorter than 30 minutes; 3) articles were not published in full in a peer-reviewed journal.

Study Selection

Figure 1 summarizes the study selection process. The initial search returned 1,917 publications. An additional record was identified as potentially relevant for this topic after inspection of the reference list of reviews and empirical articles identified. All entries were then introduced in the Rayyan web service [23] to facilitate the following steps of the study selection. After identifying 427 duplicate articles, 111 articles were selected for further inspection on the basis of their title and/or abstract. When the potential inclusion of a study was not evident, the article was discussed by all authors to reach an agreement. The final selection of all shortlisted articles was approved by all authors. Sixty-nine full articles were assessed for eligibility and 28 were included in the qualitative analysis. 22 of them reported sufficient information to compute at least one effect size for exercise performance. In total, these 22 articles contained information to compute 25 effect sizes for exercise performance variables and 20 for RPE.

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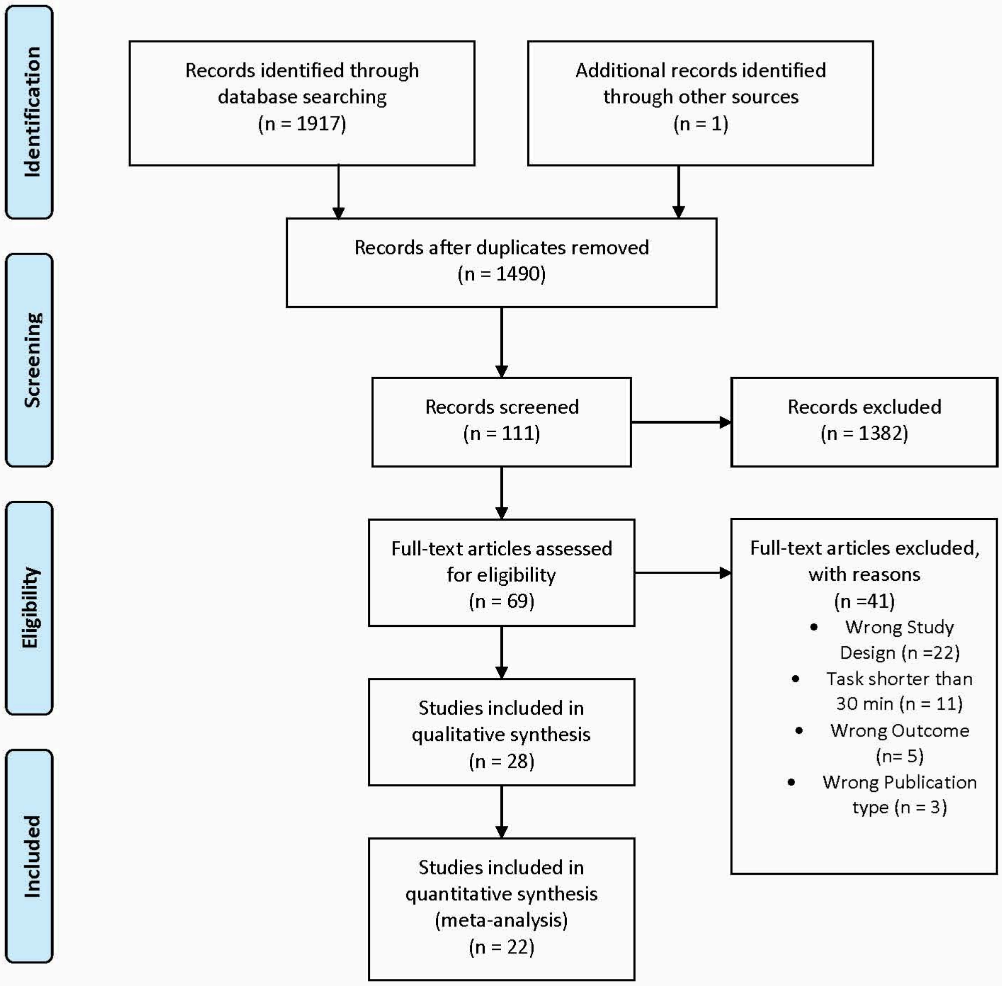

Figure 1. PRISMA summary of the study selection process

Quality Assessment of Results

We used the Physiotherapy Evidence Database (PEDro) to assess the methodological quality of the studies included in the meta-analysis [24]. None of the studies were excluded based upon their PEDro scale score (M = 6.9 ± 0.81)..

Data Extraction

Data were extracted by DH and entered into a custom excel spreadsheet, summarized in Table 1 and available at https://osf.io/s5tz6/. Given that some studies assessed two mental fatigue conditions (e.g., mental fatigue plus caffeine or mental fatigue plus heat stress [25,26]), we limited the extraction to the data for mental fatigue condition without any additional manipulation, in order to allow direct comparability between studies. Features of the collected included: 1) descriptive data; 2) study design; 3) type of experimental and control condition; 4) exercise protocol and type of test, and 5) main findings (mean and SD of the exercise performance and RPE outcomes; mean and SD post scores value for mental fatigue and motivation scales). Given the variety of experimental designs used in this literature, we decided to test the moderating roles of a series of methodological features of these studies to explore their possible impact on the effect of mental fatigue on exercise performance. These moderators were 1) the type of outcome (exercise performance vs. RPE); 2) the exercise mode: (self-paced vs. externally-paced[2]); 3) type of control condition (same cognitive task, but less demanding vs. neutral activity); 4) duration of the cognitive task (30-60 min vs. ≥60 min); 5) type of participants (recreational/physical active vs. well-trained/competitive vs. elite athletes); 6) if the intervention induced the state of mental fatigue successfully: (yes vs. no); and 7) if the intervention affected motivation: (yes vs. no).

Statistical Analysis

Our effect size estimate in all the quantitative analyses was the standardized mean difference, with positive sign for all the studies yielding worse performance (or higher RPE) in the experimental condition than in the control condition. In the pre-registered protocol, we specified that for studies using within-participants designs, we would use the standard deviation of the control condition to standardize mean differences and that we would compute the variances of these effect sizes following the equations provided by Morris and DeShon [27]. This strategy was intended to improve the comparability of effect sizes in within-participants and between-groups studies. In the end, however, all the effect sizes included in the meta-analyses came from within-participants designs. Because of this, we

[2] Self-paced exercise refers to a physical activity in which the athletes can regulate their effort throughout the test, whereas in an externally-paced exercise, intensity is fixed and athletes cannot change the pacing.

decided to use Cohen's d_z as our effect size estimate instead. The advantage of doing so is that d_z scores are computed on the basis of the same information that is used to test for statistical significance in these studies (i.e., a paired-samples *t*-test) and, consequently, the confidence intervals of the effect size are more consistent with the *p*-values reported in the original papers. Additionally, unlike the effect size estimate specified in the protocol, the computation of d_z does not require any knowledge of the correlation between dependent measures, which simplifies substantially the extraction of statistical information from the original studies. All the meta-analyses were performed using the "metafor" R package [28] and relied on random-effects models, fitted with a restricted maximum likelihood estimation algorithm.

Results

Study characteristics

The effects analysed included data from 22 studies (providing 25 statistically independent effect sizes for performance measures and 20 for RPE) and 318 participants (16% female participants). The number of participants per study ranged from 8 to 25 participants (mean = 12.7 participants, SD = 4.53). In relation to the type of participants, 12 studies employed recreational sportspeople, 9 well-trained ones, and 4 elite athletes. Of the studies included in the quantitative analysis, 15 assessed a self-paced exercise test, 7 studies used a externally-paced exercise test, and 3 others. Regarding the type of control condition, 20 studies used a neutral activity as a less demanding task condition (e.g., watching a documentary), whereas 2 used a less demanding cognitive task (e.g., Stroop task without the inhibitory component). With regard to the duration of the task, in 15 studies lasted between 30-60 minutes and in 7 studies more than 60 minutes. In 15 of the included studies induced successfully the state of subjective mental fatigue, whereas the other did not or did not measure it.

Overall Meta-Analysis

In total, we were able to compute 25 statistically independent d_z scores for performance measures. The results of the overall meta-analysis are summarized in the forest plot (Figure 2). Among them, the mean effect size was 0.48, with 95% CI [0.23, 0.73]. The meta-analysis also revealed a statistically significant amount of heterogeneity across effect sizes, $I^2 = 75.59$, $Q(24) = 87.41$, $p < .001$.

We were also able to compute 20 statistically independent d_z scores for RPE. The mean effect size for this outcome was 0.29, 95% CI [0.05, 0.54]. As in the case of objective measures, the amount of heterogeneity was statistically significant, $I^2 = 70.12$, $Q(19) = 58.77$, $p < .001$.

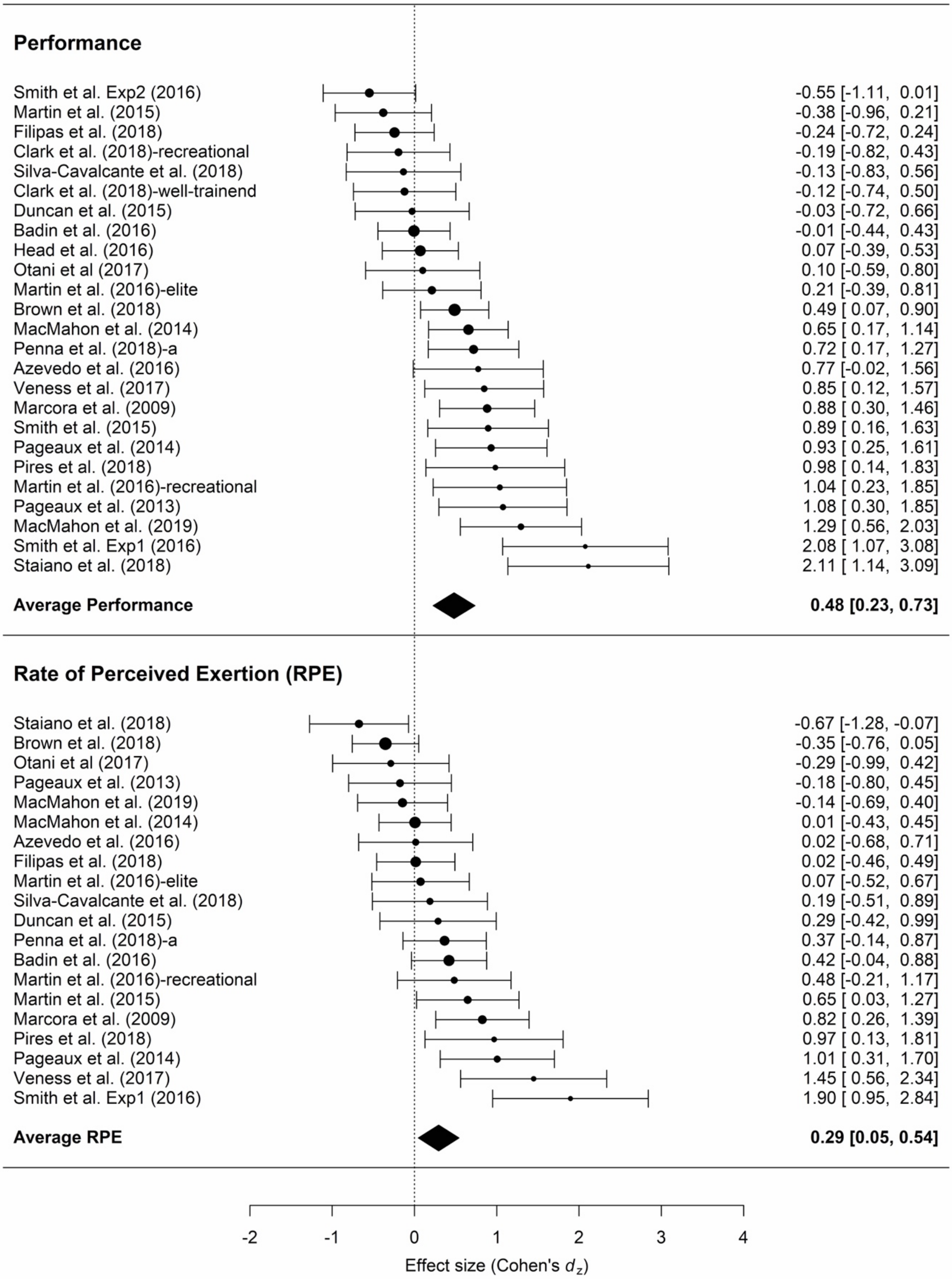

Figure 2 Forest plot of the effect size of mental fatigue on exercise performance and RPE.

Moderator and Sub-Group Analyses

To compare the relative size of objective measures of performance and RPE, we entered the 25 effect sizes of performance outcome and the 20 effect sizes of RPE into a single multivariate meta-analysis with the type of outcome (exercise performance vs. RPE) as a categorical moderator, adding a random intercept at the sample level to account for statistical dependencies between effect sizes. The moderator test revealed a significant difference between both types of outcomes, $Q_M(1) = 6.17$, $p = .013$. As can be seen in the analyses reported above, overall, mental fatigue seemed to have a larger impact on exercise performance measures than on RPE.

The remaining moderator tests were conducted solely on performance measures, as RPE measures rely on exercise performance measures. Effect sizes were moderated by the type of participants (recreational vs. well-trained vs. elite), $Q_M(2) = 6.41$, $p = .041$, with mental fatigue having stronger effects on recreational, $d_z = 0.73$, 95% CI [0.05, 1.24], and elite participants, $d_z = 0.65$, 95% CI [0.39, 1.08], than on well-trained participants, $d_z = 0.09$, 95% CI [-0.30, 0.47]. Effect sizes were also moderated by the type of exercise, $Q_M(1) = 4.77$, $p = .029$, with externally-paced exercises yielding larger effects, $d_z = 0.96$, 95% CI [0.52, 1.40], than self-paced exercise, $d_z = 0.38$, 95% CI [0.11, 0.65]. In contrast, effect sizes were not significantly moderated by the length of the fatigue-induction task (30-60 mins vs. >60 mins), $Q_M(1) = 0.003$, $p = .960$, or the type of cognitive control task (control vs. neutral), $Q_M(1) = 2.11$, $p = .146$. Similarly, effect sizes were not significantly larger for studies demonstrating significant evidence of mental fatigue, $Q_M(1) = 0.99$, $p = .320$.

Bias Analyses

The funnel plot of effect sizes analysed depicted in Figure 3 is highly asymmetric, with studies with smaller sample sizes and a higher standard error reporting substantially larger effect sizes. Egger's test for funnel plot asymmetry was highly significant, $b_1 = 5.61$, $SE_b = 1.41$, $z = 3.99$, $p < .001$. This suggests that the distribution of effect sizes might be biased by the selective publication of studies (or analyses) with statistically significant reports, and that the meta-analytic average reported above is likely to overestimate the true effects of mental fatigue on these outcomes. Moreover, the intercept of Egger's test is significantly negative $b_0 = -1.36$, $SE_b = 0.47$, $z = -2.91$, $p = .004$, a result that is commonly observed when the true effect is zero, but the studies are biased by a combination of selective publication and questionable research practices [29]. To obtain an estimate of the likely size of the effect in the absence of publication bias, we fitted a 3-parameter selection model using the weight package for R [30]. Assuming publication bias improved the fit of the model significantly, $\chi^2(1) = 5.46$, $p = .019$, and returned a non-significant bias-corrected mean effect of 0.11, 95% CI [-0.22, 0.43].

Likewise, for the RPE, Egger's regression test revealed significant evidence of funnel plot asymmetry, $b_1 = 4.89$, $SE_b = 1.51$, $z = 3.25$, $p = .001$, suggesting, again, that the meta-analytic average is likely to be biased by the selective publication of significant results. The intercept of Egger's regression test was also significantly negative, $b_0 = -1.24$, $SE_b = 0.48$, $z = -2.59$, $p = .009$. The bias-corrected average provided by the 3-parameter selection model [30] was small, $d_z = 0.20$, and non-significantly different from zero, 95% CI [-0.20, 0.60], although in this case, the model assuming publication bias did not perform significantly better than the standard random-effects model, $\chi^2(1) = 0.25$, $p = .618$.

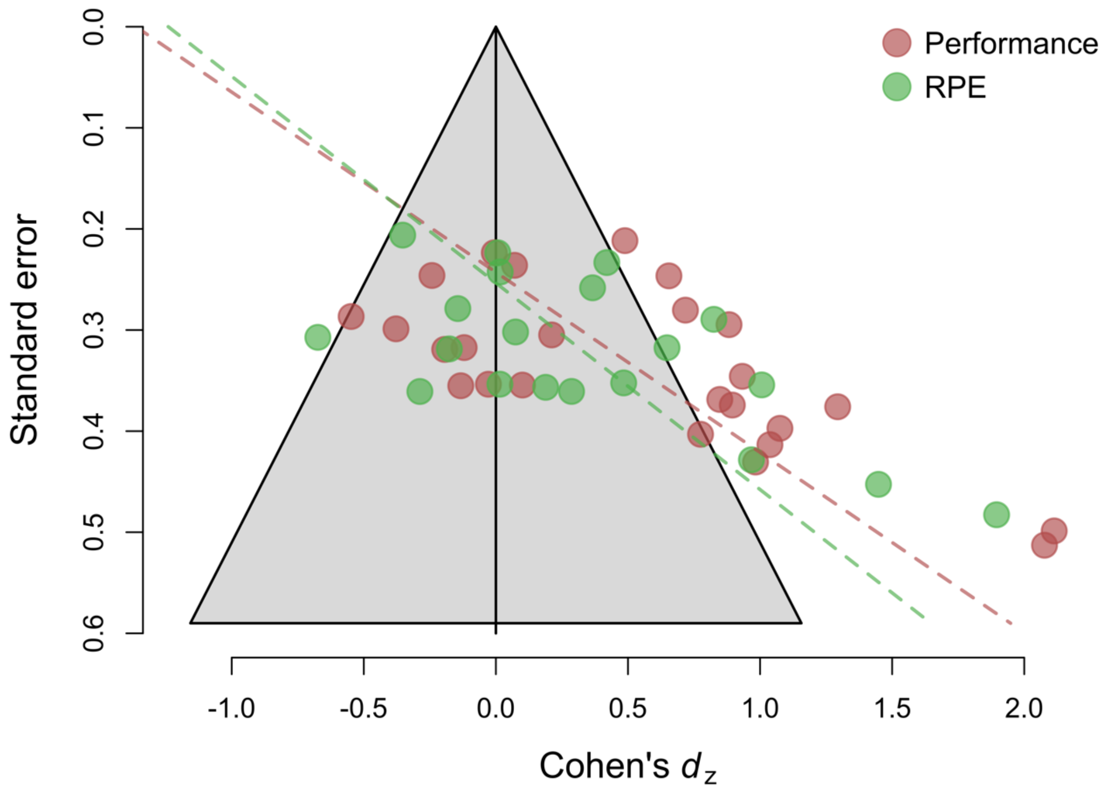

Figure 3 Funnel plot of Cohen's d_z effect size versus study standard error.

Discussion

The purpose of this systematic review and bias-sensitive meta-analysis was to assess if a state of mental fatigue induced by a long and challenging cognitive task performed before a physical exercise had a negative influence on exercise performance and RPE. Overall, although the analysis reveals a significant effect of mental fatigue on exercise performance ($d_z = 0.48$), supplementary analyses strongly suggest that this is likely to be biased by selective reporting or questionable research practices. In fact, our analyses suggest that once the effects are corrected for publication bias, the resulting average might not be significantly different from zero. Likewise, mental fatigue had a negative influence on RPE ($d_z = 0.29$), but again the results are probably biased and not significantly different from zero once corrected for bias. Therefore, our results do not support the hypothesis that mental fatigue has a negative influence on a subsequent physical exercise or in RPE. These results are in consonance with those of McMorris et al. [21], who also pointed out that the negative effects of mental fatigue (if any) are more likely due to random error rather than to a true effect.

The starting hypothesis of this literature is that performing a cognitive task involving executive functions (such as response inhibition, sustained attention or working memory) for at least 30 minutes increases the subjective feeling of tiredness and lack of energy, leading to a state of mental fatigue. This implies that cognitive tasks and physical performance share a common pool of cognitive resources or mental energy. From this point of view, the studies on mental fatigue and physical performance bear some resemblance to research conducted in the domain of ego depletion [6]. These studies are based on the idea that all acts of willpower and self-regulation deplete a limited pool of resources. Although this theory has been the cornerstone of more than 20 decades of research on self-control, the hypothesis that self-control is limited is currently losing much of its credibility, due to the obvious signs of bias in this literature [31] and a prominent failure to replicate the basic ego depletion effect in a multi-lab study comprising more than 2,000 participants [32]. The field of sport science is not exempt from these problems. Recently, there has been a call to adopt more transparent measures to improve the quality of research [33]. Together with the publication bias aforementioned, p-hacking, data dredging and HARKing are common instances of questionable bad practices in this literature.

Unfortunately, although the presence of biases in this literature did not allow us to clarify if there is a link between mental fatigue and exercise performance, we cannot discard completely that mental fatigue has a negative influence on exercise either. We have identified a series of factors that should be considered in future studies on this topic. Given that expert participants might have reached higher levels of automaticity, mental demands for performing exercise might be reduced in them. Therefore, mental fatigue induced in a lab-setting might have a lower influence on exercise performance in these participants [34]. Moreover, much of the mental fatigue research has focused on acute intervention studies, but little is known about the accumulation of mental fatigue over consecutive days. The absence of clear effects might be due to the low levels of mental fatigue accumulated in a single acute session. If so, it would be necessary to bring under several days of mental fatigue [35]. Similarly, self-paced and externally-paced exercise modalities might be affected differently by mental fatigue, given that they may request different cognitive processes [36]. The question of whether performance decrement is related to a rise on RPE or to participants' unwillingness to put effort on a physical exercise (i.e, reduced motivation) also remains to be elucidated [37,38]. In addition, the control conditions do not usually involve any cognitive activity (e.g., watching documentaries or seating) and the effects of the cognitive task (if any) on exercise performance might be due to the mere effect of doing a cognitive task versus doing nothing. Finally, most of the studies failed to detect a subjective feeling of mental fatigue. Thus, additional measures should be included to guarantee the success of the intervention.

Conclusion

The results of the current meta-analysis raise intriguing questions regarding the nature and extent of the effects of mental fatigue on exercise. In light of the reporting biases in this literature, it is difficult to draw any firm conclusion about the link between mental fatigue and exercise performance or perceived exertion. Beyond hypothesis and mechanisms behind the possible negative influence of mental fatigue on exercise performance, researchers on this topic should endorse sound scientific practises. Study' pre-registration and data sharing might help substantially to reduce the likelihood of p-hacking, publication bias and HARKing, which so far seem to be influencing this literature.

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Compliance with ethical standards

Contributors: All authors have made substantial contributions to various elements of the study.

Conceptualization: Darías Holgado, Daniel Sanabria, José C. Perales, and Miguel A. Vadillo

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Conflict of interests: none declared

Data availability

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Data and code for the meta-analysis can be found here: https://osf.io/s5tz6/

References

1. Proske U, Gandevia SC. The Proprioceptive Senses: Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force. Physiol Rev. 2012;92:1651–97.

2. Baron B, Moullan F, Deruelle F, Noakes TD. The role of emotions on pacing strategies and performance in middle and long duration sport events. Br J Sports Med. 2011;45:511–7.

3. Verhoeven K, Van Damme S, Eccleston C, Van Ryckeghem DML, Legrain V, Crombez G. Distraction from pain and executive functioning: an experimental investigation of the role of inhibition, task switching and working memory. Eur J Pain Lond Engl. 2011;15:866–73.

4. Audiffren M, André N. The strength model of self-control revisited: Linking acute and chronic effects of exercise on executive functions. J Sport Health Sci. 2015;4:30–46.

5. Inzlicht M, Schmeichel BJ, Macrae CN. Why self-control seems (but may not be) limited. Trends Cogn Sci. 2014;18:127–33.

6. Baumeister RF, Bratslavsky E, Muraven M, Tice DM. Ego depletion: is the active self a limited resource? J Pers Soc Psychol. 1998;74:1252–65.

7. Cutsem JV, Marcora S, Pauw KD, Bailey S, Meeusen R, Roelands B. The Effects of Mental Fatigue on Physical Performance: A Systematic Review. Sports Med. 2017;47:1569–88.

8. Pageaux B, Lepers R. Chapter 16 - The effects of mental fatigue on sport-related performance. In: Marcora S, Sarkar M, editors. Prog Brain Res. Elsevier; 2018. p. 291–315.

9. Ishii A, Tanaka M, Watanabe Y. Neural mechanisms of mental fatigue. Rev Neurosci. 2014;25:469–79.

10. Mizuno K, Tanaka M, Yamaguti K, Kajimoto O, Kuratsune H, Watanabe Y. Mental fatigue caused by prolonged cognitive load associated with sympathetic hyperactivity. Behav Brain Funct BBF. 2011;7:17.

11. Brownsberger J, Edwards A, Crowther R, Cottrell D. Impact of mental fatigue on self-paced exercise. Int J Sports Med. 2013;34:1029–36.

12. Wang C, Trongnetrpunya A, Babu I, Samuel H, Ding M, Kluger BM. Compensatory Neural Activity in Response to Cognitive Fatigue. 2016;36:3919–24.

13. Boksem M, Tops M. Mental fatigue: costs and benefits. Brain Res Rev. 2008;59:125–39.

14. Barch DM, Braver TS, Nystrom LE, Forman SD, Noll DC, Cohen JD. Dissociating working memory from task difficulty in human prefrontal cortex. Neuropsychologia. 1997;35:1373–80.

15. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. J Appl Physiol. 2009;106:857–64.

16. Pires FO, Silva-Júnior FL, Brietzke C, Franco-Alvarenga PE, Pinheiro FA, de França NM, et al. Mental Fatigue Alters Cortical Activation and Psychological Responses, Impairing Performance in a Distance-Based Cycling Trial. Front Physiol. 2018;9.

17. MacMahon C, Schücker L, Hagemann N, Strauss B. Cognitive fatigue effects on physical performance during running. J Sport Exerc Psychol. 2014;36:375–81.

18. Head JR, Tenan MS, Tweedell AJ, Price TF, LaFiandra ME, Helton WS. Cognitive fatigue influences time-on-task during bodyweight resistance training exercise. Front Physiol 2016;7.

19. Van Cutsem J, De Pauw K, Buyse L, Marcora S, Meeusen R, Roelands B. Effects of mental fatigue on endurance performance in the heat. Med Sci Sports Exerc. 2017;49:1677–87.

20. Silva-Cavalcante MD, Couto PG, Azevedo RA, Silva RG, Coelho DB, Lima-Silva AE, et al. Mental fatigue does not alter performance or neuromuscular fatigue development during self-paced exercise in recreationally trained cyclists. Eur J Appl Physiol. 2018;118:2477–87.

21. McMorris T, Barwood M, Hale BJ, Dicks M, Corbett J. Cognitive fatigue effects on physical performance: A systematic review and meta-analysis. Physiol Behav. 2018;188:103–7.

22. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ. 2009;339:b2535.

23. Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. Rayyan—a web and mobile app for systematic reviews. Syst Rev [Internet]. 2016;5. Available from: https://search.proquest.com/docview/1846429327

24. Verhagen AP, de Vet HC, de Bie RA, Kessels AG, Boers M, Bouter LM, et al. The Delphi list: a criteria list for quality assessment of randomized clinical trials for conducting systematic reviews developed by Delphi consensus. J Clin Epidemiol. 1998;51:1235–41.

25. Azevedo R, Silva-Cavalcante MD, Gualano B, Lima-Silva AE, Bertuzzi R. Effects of caffeine ingestion on endurance performance in mentally fatigued individuals. Eur J Appl Physiol. 2016;116:2293–303.

26. Otani H, Kaya M, Tamaki A, Watson P. Separate and combined effects of exposure to heat stress and mental fatigue on endurance exercise capacity in the heat. Eur J Appl Physiol. 2017;117:119–29.

27. Morris SB, DeShon RP. Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. Psychol Methods. 2002;7:105–25.

28. Viechtbauer W. Conducting Meta-Analyses in R with the metafor Package. J Stat Softw. 2010;
29. Carter EC, Schönbrodt FD, Gervais WM, Hilgard J. Correcting for Bias in Psychology: A Comparison of Meta-Analytic Methods. Adv Methods Pract Psychol Sci. 2019;2:115–44.

30. Vevea JL, Hedges LV. A general linear model for estimating effect size in the presence of publication bias. Psychometrika. 1995;60:419–35.

31. Carter EC, McCullough ME. Publication bias and the limited strength model of self-control: has the evidence for ego depletion been overestimated? Front Psychol. 2014; 5.

32. Hagger MS, Chatzisarantis NLD, Alberts H, Anggono CO, Batailler C, Birt AR, et al. A Multilab Preregistered Replication of the Ego-Depletion Effect. Perspect Psychol Sci J Assoc Psychol Sci. 2016;11:546–73.

33. Caldwell A, Vigotsky AD, Nuckols G, Boardley I, Schmidt J, Tenan M, et al. Moving Sport and Exercise Science Forward: A Call for the Adoption of More Transparent Research Practices. SportRxiv; 2019 Jan. Available from: https://osf.io/fxe7a

34. Russell S, Jenkins D, Smith M, Halson S, Kelly V. The application of mental fatigue research to elite team sport performance: New perspectives. Journal of Science and Medicine in Sport. 2019. 22(6) 723-728.

35. Russell S, Jenkins D, Rynne S, Halson SL, Kelly V. What is mental fatigue in elite sport? Perceptions from athletes and staff. Eur J Sport Sci. 2019;1–10.

36. Marino FE. The limitations of the constant load and self-paced exercise models of exercise physiology. Comp Exerc Physiol. 2012;8:3–9.

37. Martin K, Meeusen R, Thompson KG, Keegan R, Rattray B. Mental Fatigue Impairs Endurance Performance: A Physiological Explanation. Sports Med. 2018;

38. Schiphof-Godart L, Roelands B, Hettinga FJ. Drive in sports: How mental fatigue affects endurance performance. Front Psychol. 2018;9.

39. Pageaux B, Marcora SM, Lepers R. Prolonged mental exertion does not alter neuromuscular function of the knee extensors. Med Sci Sports Exerc. 2013;45:2254–64.

40. Pageaux B, Lepers R, Dietz KC, Marcora SM. Response inhibition impairs subsequent self-paced endurance performance. Eur J Appl Physiol. 2014;114:1095–105.

41. Duncan MJ, Fowler N, George O, Joyce S, Hankey J. Mental fatigue negatively influences manual dexterity and anticipation timing but not repeated high-intensity exercise performance in trained adults. Res Sports Med. 2015;23:1–13.

42. Martin K, Thompson KG, Keegan R, Ball N, Rattray B. Mental fatigue does not affect maximal anaerobic exercise performance. Eur J Appl Physiol. 2015;115:715–25.

43. Smith MR, Marcora SM, Coutts AJ. Mental fatigue impairs intermittent running performance. Med Sci Sports Exerc. 2015;47:1682–90.

44. Badin OO, Smith MR, Conte D, Coutts AJ. Mental fatigue: Impairment of technical performance in small-sided soccer games. Int J Sports Physiol Perform. 2016;11:1100–5.

45. Martin K, Staiano W, Menaspà P, Hennessey T, Marcora S, Keegan R, et al. Superior Inhibitory Control and Resistance to Mental Fatigue in Professional Road Cyclists. PLOS ONE. 2016;11:e0159907.

46. Smith MR, Coutts AJ, Merlini M, Deprez D, Lenoir M, Marcora SM. Mental fatigue impairs soccer-specific physical and technical performance. Med Sci Sports Exerc. 2016;48:267–76.

47. Veness D, Patterson SD, Jeffries O, Waldron M. The effects of mental fatigue on cricket-relevant performance among elite players. J Sports Sci. 2017;35:2461–7.

48. Vrijkotte S, Meeusen R, Vandervaeren C, Buyse L, Van Cutsem J, Pattyn N, et al. Mental fatigue and physical and cognitive performance during a 2-bout exercise test. Int J Sports Physiol Perform. 2018;13:510–6.

49. Brown DMY, Bray SR. Effects of Mental Fatigue on Exercise Intentions and Behavior. Ann Behav Med. 2019;53:405–14.

50. Clark IE, Goulding RP, DiMenna FJ, Bailey SJ, Jones MI, Fulford J, et al. Time-trial performance is not impaired in either competitive athletes or untrained individuals following a prolonged cognitive task. Eur J Appl Physiol. 2019;119:149–61.

51. Filipas L, Mottola F, Tagliabue G, La Torre A. The effect of mentally demanding cognitive tasks on rowing performance in young athletes. Psychol Sport Exerc. 2018;39:52–62.

52. Penna EM, Filho E, Wanner SP, Campos BT, Quinan GR, Mendes TT, et al. Mental Fatigue Impairs Physical Performance in Young Swimmers. Pediatr Exerc Sci. 2018;30:208–15.

53. Penna EM, Filho E, Campos BT, Pires DA, Nakamura FY, Mendes TT, et al. Mental fatigue does not affect heart rate recovery but impairs performance in handball players. Rev Bras Med Esporte. 2018;24:347–51.

54. Slimani M, Znazen H, Bragazzi NL, Zguira MS, Tod D. The Effect of Mental Fatigue on Cognitive and Aerobic Performance in Adolescent Active Endurance Athletes: Insights from a Randomized Counterbalanced, Cross-Over Trial. J Clin Med. 2018;7:510.

55. Staiano W, Bosio A, Piazza G, Romagnoli M, Invernizzi PL. Kayaking performance is altered in mentally fatigued young elite athletes. J Sports Med Phys Fitness. 2018;

56. Salam H, Marcora SM, Hopker JG. The effect of mental fatigue on critical power during cycling exercise. Eur J Appl Physiol. 2018;118:85–92.

57. MacMahon C, Hawkins Z, Schücker L. Beep Test Performance Is Influenced by 30 Minutes of Cognitive Work. Med Sci Sports Exerc. 2019;

Table 1. Studies examining the effects of mental fatigue on exercise performance. Studies not included in quantitative meta-analysis are marked with *. TTE: Time to exhaustion test; MVC: Maximal voluntary contraction test; TT: Time-trial. LSPT: Loughborough soccer passing test.

Reference	Participants	N	Experimental task	Control task	Type of exercise	Test	Measure	↓Performance	↑RPE	Mental fatigue
Marcora et al. (2009)[15]	**Recreational**	**18**	**90min-AX-CPT**	**90min-documentary**	**Externally-paced**	**Cycling TTE 80%**	**Time**	**Yes**	**Yes**	**Yes**
Brownsberger et al. (2013) [11]*	**Recreational**	**12**	**90min-AX-CPT**	**90min-documentary**	**Self-paced**	**Cycling TT-10min RPE 15**	**Power output**	**Yes**	**-**	**Yes**
Pageaux et al. (2013) [39]	**Recreational**	**8**	**90min-AX-CPT**	**90min-documentary**	**Externally-paced**	**MVC-TTE**	**Time**	**Yes**	**No**	**Yes**
MacMahon et al. (2014) [17]	**Well-trained**	**16**	**90min-AX-CPT**	**90min-documentary**	**Self-paced**	**Running TT-3km**	**Time**	**Yes**	**No**	**No**
Pageaux et al. (2014) [40]	**Recreational**	**20**	**30min-Stroop**	**30min-Stroop-control**	**Self-paced**	**Running TT-5km**	**Time**	**Yes**	**Yes**	**No**
Duncan et al. (2015) [41]	**Well-trained**	**8**	**40min-Sustained Attention**	**40min-documentary**	**Self-paced**	**Cycling 30seg Wingate**	**Power output**	**No**	**No**	**Na**

Martin et al. (2015) [42]	**Well-trained**	**16**	**90min-AX-CPT**	**90min-documentary**	**Self-paced**	**Cycling 3min all-out**	**Power output**	**No**	**Yes**	**No**
Smith et al. (2015) [43]	**Well-trained**	**10**	**90min-AX-CPT**	**90min-documentary**	**Self-paced**	**Running TT-45min**	**Distance**	**Yes**	**Yes**	**Yes**
Azevedo et al. (2016) [25]	**Recreational**	**12**	**90min-AX-CPT**	**90min-documentary**	**Externally-paced**	**Cycling TTE 80%**	**Time**	**No**	**No**	**No**
Badin et al. (2016) [44]	**Elite**	**12**	**30min-Stroop**	**30min-documentary**	**Other**	**Small side game**	**Distance**	**No**	**No**	**No**
Head et al. (2016) [18]	**Recreational**	**17**	**52min-Go/NoGo**	**52min-documentary**	**Self-paced**	**20min Body resistance exercise**	**Repetitions**	**Yes**	**-**	**Yes**
Martin et al. (2016) [45]	**Elite**	**11**	**30min-Stroop**	**10 min seated**	**Self-paced**	**Cycling TT-20min**	**Power output**	**No**	**No**	**No**
Martin et al. (2016) [45]	**Recreational**	**9**	**30min-Stroop**	**10 min seated**	**Self-paced**	**Cycling TT-20min**	**Power output**	**Yes**	**No**	**Yes**
Smith et al. Exp1 (2016) [46]	**Recreational**	**12**	**30min-Stroop**	**30min-seated**	**Externally-paced**	**Running (Yo-Yo test)**	**Distance**	**Yes**	**Yes**	**Yes**

Smith et al. Exp2 (2016) [46]	Well-trained	14	30min-Stroop	30min-seated	Other	LSPT	Time	No	-	Yes
Otani et al (2017) [26]	Recreational	20	90min Stroop/ Sternberg/Rapid visual information	90min-documentary	Externally-paced	Cycling TTE 80%	Time	Yes	No	Yes
Van Cutsem et al. (2017) [19]*	Well-trained	10	45min-Stroop	45min Documentary	Self-paced	Cycling TTE-15min 80%	Time	No	No	Yes
Veness et al. (2017) [47]	Elite	10	30min-Stroop	30min reading	Externally-paced	Running (Yo-Yo test)	Distance	Yes	Yes	
Vrijkotte et al. (2018) [48]*	Well-trained	9	90min-Stroop	90min-seated	Externally-paced	Cycling Incremental test	Power output	No	No	Yes
Brown et al. (2018) [49]	Recreational	25	50min-AX-CPT	50min documentary	Self-paced	Cycling TT-30min	Total work (Kj)	Yes	No	Yes
Clark et al. (2018) [50]	Well-trained	10	30min-Stroop	30 min documentary	Self-paced	Cycling TT-6min	Total work (Kj)	No	-	Na
Clark et al. (2018) [50]	Recreational	10	30min-Stroop/n-back	30 min documentary	Self-paced	Cycling TT-6min	Total work (Kj)	No	.	Na

Filipas et al. (2018) [51]	Well-trained	8	60min-Stroop	60min-painting	Self-paced	Rowing TT-1500m	Time	No	No	Yes
Penna et al. (2018)-a [52]	Well-trained	8	30min-Stroop	30min-documentary	Self-paced	Swimming TT-1500m	Time	Yes	No	Yes
Penna et al. (2018)-b [53]*	Well-trained	12	30min-Stroop	30min-documentary	Externally-paced	Running Yo-Yo test	Distance	Yes	-	Yes
Pires et al. (2018) [16]	Recreational	12	30min Rapid Visual Information Processing (RVP) Test	30min-seated	Self-paced	Cycling TT-20km	Power output	Yes	Yes	Yes
Silva-Cavalcante et al. (2018) [20]	Well-trained	8	90min-AX-CPT	90min-documentary	Self-paced	Cycling TT_4km	Time	No	No	Yes
Slimani et al. (2018) [54]*	Well-trained	10	30min-Stroop	30min reading	Externally-paced	Running (shuttle test)	Distance	Yes	Yes	Yes
Staiano et al. (2018) [55]	Elite	13	60min-Stroop	60min-documentary	Self-paced	Kayaking TT-2000m	Time	Yes	No	Yes
Salam et al. (2018) [56]*	Well-trained	10	30min-Stroop	30min-seated	Externally-paced	Cycling TTE 100%	Time	Na	-	Yes

MacMahon et al. (2019) [57]	**Recreational**	**13**	**30min-Stroop**	**30min-Stroop-control**	**Externally-paced**	**Running shuttle test**	**Time**	**Yes**	**No**	**Yes**